

# **Bridging the Divide between Air Quality Monitoring, Management and Policy in the Sea-to-Sky Airshed**

A method for analyzing and interpreting large volume air quality data  
for management and policy guidance

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## **Abstract**

Air pollution has increasingly been the focus of management and policy efforts since the early 1950s. Networks of monitoring stations for data to inform, create, focus, assess and improve air pollution management and policy. However, monitoring systems can become disconnected from air quality management and policy without analysis and interpretation to bridge the divide. This thesis develops a method of analyzing and interpreting large volume air quality data into key air pollutant trends and characteristics to guide air quality management and policy. The method is applied to air quality data between 2002 and 2013 in the Sea-to-Sky Airshed, located in south-western British Columbia, Canada. At the time of study, this airshed contained a monitoring system that had been growing increasingly disconnected from the airshed's air quality management and policy. Applying this method uncovered significant instances of inaccurate and missing air quality data, and identified the airshed's key pollutant trends and characteristics. These findings were then used to create recommendations for improving the resource efficiency and quality of the airshed's monitoring, management and policy. Also identified were applications of R and R's OpenAir package which are estimated to significantly reduce analysis time and offer additional analysis options.

**Keywords:** air quality, air pollution, analysis, Sea-to-Sky, Canada



## **Executive Summary**

Air pollution involves chemical, mechanical and biological agents that modify the environment of indoor and outdoor air from its original state. Over the past century, and in particular after the 1952 London Smog incident, air pollution has gained prominence in management, policy research and public spheres. While air pollution levels have generally decreased since this period (particularly in developed regions) through policy and management efforts and shifts away from industry, air pollution problems persist. Recent research continues to link both high and low levels of air pollution to a host of health, economic, and environmental impacts.

Policy and management for improving air quality typically depend on monitoring networks of stations that measure and record levels of air pollutants. These measurements are used for identifying emission sources, determining the range and impact of emissions, assessing the impacts of policies, evaluating the efficacy of air quality management, and for making improvements to existing efforts to reduce pollution levels. However, the connection between monitoring, management and policy is not intrinsic. Monitoring activities generate large volumes of data, and this must first be analyzed and interpreted before being of use to management and policy efforts. The Sea-to-Sky Airshed, located north of Vancouver in British Columbia, Canada, illustrates such a case.

Despite the importance of pristine air quality for supporting the region's outdoor tourism and safeguarding human health, comprehensive analysis and interpretation of air quality data has not occurred since 2001. This has created a growing gap between airshed monitoring and airshed management and policy and also a growing potential to improve their efficiency and effectiveness. The following thesis aims to bridge this divide by analyzing air pollution data collected between 2002 and 2013 and to interpret the measurements into guidance for optimizing airshed monitoring, management and policy.

To do so, a method of analyzing and interpreting large air quality data sets into management and policy guidance was necessary. The author developed a method based on a literature analysis of existing academic literature and recent air quality summary reports, analytical software manuals, statistical guidance from a professor from Quest University Canada, and regular consultation with an air quality specialist from the British Columbia Ministry of Environment (MoE) responsible for overseeing the Sea-to-Sky airshed. The method consists of:

1. Establishing background information for the airshed's geography, monitoring network, management, policy, key emission sources, and key pressures on air quality;
  - a. Conduct a monitoring network tour to gain overview on stations and background on policies, operating procedures and data collection
2. Verifying data completeness and accuracy using station summaries, boxplots and histograms;
3. Developing an overview of stations and data using station summaries and identifying which measurements to include and exclude;
4. Analyzing the air quality readings using station summaries, air quality objectives, boxplots, autocorrelation plots, seasonal-trend decomposition procedure by Loess,

percentile plots, time variation plots, average hourly concentration plots, and pollution roses;

5. Extracting of key findings using 4 criteria based on ambient air quality objectives

\* Maintain interactions with key stakeholders throughout the process for troubleshooting and dialogue

This method was applied to carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), ground level ozone (O<sub>3</sub>), fine particulate matter with a mass median diameter of less than 2.5 microns (PM<sub>2.5</sub>), inhalable particulate matter with a mass median diameter of less than 10 microns and larger than 2.5 microns (PM<sub>10</sub>), sulphur dioxide (SO<sub>2</sub>) and total reduced sulphur (TRS) measurements.

Applying the method yielded instances of inaccurate and missing meteorological and air pollution data. Identifying these issues led to corrections and additions of data on the publically available British Columbian Envista Air Database, and the correction of an instrument recording inaccurate wind direction data.

Analyzing the air contaminant data with the method also revealed the following key trends and characteristics for guiding management and policy of the Sea-to-Sky Airshed:

| Contaminant       | Station       | Exceedances                       | Trend | Characteristics  | Priority   |
|-------------------|---------------|-----------------------------------|-------|--|------------|
| O <sub>3</sub>    | Squamish      | 3                                 | →     | Spring afternoon   | High       |
|                   | Whistler      | Just under                        | →     | Spring Afternoon   | High       |
| PM <sub>2.5</sub> | Langdale      | Just under                        | →     | Mid-day peak   | High       |
|                   | Squamish      | Just under                        | →     | Main peak Saturday midnight<br>Second largest peaks are daily at late morning and midnight<br>Marginal July-Sept. Peak | High       |
|                   | Whistler      | Just under                        | →     | Midnight peaks, especially on Saturdays<br>Marginal December Peak  | High       |
|                   | Horseshoe Bay | Just under, but less than others  | →     | Marginal midnight peaks  | Mid-High   |
| PM <sub>10</sub>  | Langdale      | 0                                 | →     | Insignificant  | Low        |
|                   | Squamish      | 2                                 | →     | 8 to 9 pm during summer  | High       |
| TRS               | Langdale      | 238                               | →     | Stochastic events  | Medium     |
|                   | Squamish      | 18                                | →     | Stochastic events, TRS originates from North of station during low winds   | Medium-low |
| NO <sub>2</sub>   | Langdale      | 1/4 <sup>th</sup> under objective | →     | Insignificant  | Low        |
|                   | Squamish      |                                   | →     | Insignificant  |            |
|                   | Whistler      |                                   | ↘     | Marginal January peak<br>Marginal Friday 9 pm peak   |            |
| CO                | Horseshoe Bay | Well under objective              | ↘     | Weekdays between 8 to 9 pm<br>Weekend afternoons and 7 to 9 pm   | Low        |
| SO <sub>2</sub>   | Langdale      | Well under objective              | →     | Insignificant  | Low        |
|                   | Squamish      |                                   | →     | Insignificant  |            |
| NO                | Langdale      | No objective,                     | →     | Daily peak at 8 to 9 am  | Low        |

|   |          |            |   |   |  |
|---|----------|------------|---|---|--|
|   |          | low levels |   | Levels high during calm wind            |  |
|   | Squamish |            | → | Daily peak at 8 to 9 am                 |  |
|   | Whistler |            | ↘ | Daily peak at 8 to 9 am<br>January peak |  |
| <i>Mobile Whistler Function Junction Station not applicable</i> |          |            |   |   |  |

Based on the identified trends and characteristics, the following monitoring improvements are recommended for improving the resource efficiency of air quality management:

- Add meteorological monitoring to the Whistler air quality monitoring station. The lack of information undermines management responses (particularly of PM<sub>2.5</sub>) since concrete sources cannot be qualitatively identified due to absent wind direction data.
- It is advised to consider resuming PM<sub>10</sub> monitoring or shifting the PM<sub>10</sub> monitoring from Langdale to Squamish given that 3 exceedances occurred the year prior to the cessation of monitoring. Moreover, there appears to be a small upswing in PM<sub>10</sub>'s lowest readings, indicating a possible growth in everyday emissions. Measurement stopped before enough years could confirm such a trend.
- When implementing mobile monitoring stations such as the mobile Whistler Function Junction station, ensure that the monitoring performed matches the monitoring objective (and that there are indeed explicit objectives at the onset). Otherwise, resources are wasted when data are insufficient to support the objective(s).
- Institute QA/QC policy on industry administered stations so that data is not thrown out of studies based on unreliable readings. Station audits and calibration policy would also boost legitimacy. Ultimately, these actions should reduce wasted resources and improve the data network.
- Run several basic operations for data checks once per month. With R coding templates this process should take several hours at most. This will ensure that data within the database is of higher quality, that inaccurate measurements are not recorded for months (or years!), should simplify troubleshooting when problems arise, and finally, should decrease time spent by ministry staff when completing the annual data QA/QC.
- Perform more regular instrument calibration. This can be ensured by checking that technicians follow ministry calibration guidelines. More regular calibration prevents issues such as 14 years plus of inaccurate Squamish wind direction readings, and the resulting work spent attempting to salvage the readings.

For enhancing the efficiency and effectiveness of management and policy the following actions are recommended:

- O<sub>3</sub>, PM<sub>2.5</sub> and Squamish PM<sub>10</sub> should be the focus of management efforts since levels exceed or approach ambient air quality objectives. TRS is of medium priority.
- Re-allocate time and resources from low priority areas identified in table 7-1 to high priority areas. Re-aligning air quality management strategy within the ministry and Sea-to-Sky Clean Air Society could drive such a process.
- Since the Howe Sound Pulp and Paper mill has been identified in the past as the main source of TRS in Langdale, obtaining the emissions logs can verify that they are still the key source and key actions for reducing the high amount of TRS exceedances in Langdale. Working with the mill to reduce emissions, or implementing permits or fines could further address this issue.

- Use R and R's OpenAir package for data analysis. This software completes operations and graphs in a fraction of the time as Microsoft Excel and supports a wider range of analysis. While the initial step (creating code templates) is the most time consuming part of the process, contracting out this task, or dedicating in-house personnel with more advanced R capabilities can address this barrier to implementation. After this first step, using the code requires little knowledge. One workshop would suffice to train users. Given the significant time savings, expanded capabilities and ease of use it is recommended to apply this software not only to the airshed, but on a province-wide scale.
- Complete an emission inventory. While this analysis yielded general information about trends and characteristics, it was beyond this report's scope to make an accounting of pollutant sources. Sources are necessary to further focus air quality management strategy
- Complete a dispersion analysis. This is necessary to plot the movement of pollutants into, out of and throughout the airshed. However, the quality of such an analysis depends on whether additional high quality MET data can be found.
- Complete regular smaller studies (annual preferably) and longer term summaries with a temporal scale similar to this study. This balances more frequent information for evaluating and adapting monitoring and management with comprehensive reflection for reflecting, re-prioritizing and re-strategizing.

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## Abbreviations

|                          |  |
|--------------------------|--|
| ACF                      | autocorrelation function   |
| AQCC                     | Air Quality Coordinating Committee   |
| AQHI                     | Air Quality Health Index   |
| AQMP                     | air quality management plan  |
| AQMS                     | air quality management system  |
| BAM                      | beta attenuated monitor (PM monitor)   |
| B.C.                     | the Canadian province of British Columbia  |
| CCME                     | Canadian Council of Ministers of the Environment   |
| CO                       | carbon monoxide  |
| GHG                      | greenhouse gas   |
| MET                      | meteorological   |
| $\mu\text{g}/\text{m}^3$ | microgram per cubic meter  |
| MoE                      | BC Ministry of Environment   |
| NO                       | nitric oxide   |
| NO <sub>2</sub>          | nitrogen dioxide   |
| NO <sub>x</sub>          | nitric oxide and nitrogen dioxide  |
| O <sub>3</sub>           | ground level ozone   |
| PM                       | airborne particulate matter  |
| PM <sub>2.5</sub>        | fine particulate matter with a mass median diameter of less than 2.5 microns                       |
| PM <sub>10</sub>         | inhalable particulate matter with a mass median diameter of more than 2.5 but less than 10 microns |
| ppb                      | parts per billion  |
| QA/QC                    | quality assurance and quality control  |
| SO <sub>2</sub>          | sulphur dioxide  |
| SO <sub>x</sub>          | sulphur oxides   |
| SSCAS                    | Sea-to-Sky Clean Air Society   |
| STL                      | seasonal trend decomposition procedure based on Loess  |
| TEOM                     | tapered element oscillating microbalance (PM monitor)  |
| TRS                      | total reduced sulphur  |

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WHO World Health Organization

# 1 Introduction

The World Health Organization (WHO) defines air pollution as the “contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere” (WHO 2014a). Typical sources of air pollution are vehicles, industrial operations, forest fires and residential wood combustion (WHO 2014). The industrial revolution marked the beginning of centuries of deteriorating air quality, especially within urban centers (Kuhlbusch et al. 2014). It was only during the last century that several large scale deadly pollution incidents elevated the priority of managing air pollution. The 1952 London Smog incident is one of the most infamous early pollution episodes. Between December 5<sup>th</sup> and 9<sup>th</sup>, thick smog settled about London; subsequently an estimated 22,000 deaths between December 1952 and February 1953 have been attributed to this pollution episode (Bell and Davis 2001).

Although overall air quality levels in developed regions have significantly improved due to management strategies and transitions away from industrialization (Kuhlbusch et al. 2014), air quality continues to be a major health concern. As an example, long term exposure to relatively low concentrations of particulate matter, elemental carbon and nitrogen dioxide, have been linked to an increased risk of mortality and cardiovascular and respiratory complications (Hoek et al. 2013). Raaschou-Nielsen et al. (2013) have associated exposure to fine particulate matter to increased risk of lung cancer. Worldwide, the WHO has attributed 1 out of 8 total deaths to air pollution, making air pollution the foremost environmental health risk (WHO 2014b).

Air pollution also exacts an economic toll. In the U.S., the cost of federal air pollution policies totaled more than \$80 billion in 2010 alone (Bell et al. 2011). Across Europe, Pascal et al. (2013) have estimated that 33 billion euros could be saved annually by complying with the WHO’s PM<sub>10</sub> guideline of 10 µg/m<sup>3</sup>. These savings arise from reduced health expenditures, employment absenteeism, and intangible costs inclusive of well-being and life expectancy. Pollution has also been linked to a reduction of vegetation growth in natural ecosystems, harvestable forests and in agricultural crops (Fiscus et al. 2005, EEA 2014).

Assessing and responding to such impacts is not possible without air quality measurements, analysis and interpretation. Monitoring networks are the most commonly used system for obtaining such data (Marc et al. 2015). These regional networks are established to collect reliable air quality information that is used as a basis for identifying emission sources, the range and impact of emissions, and assessing the impacts of policies and efficacy of air quality management (Marc et al. 2015).

Across Canada, such tasks are supported by a patchwork of air quality monitoring networks. These networks are important. Although Canada, a country oft associated with pristine wilderness; many of its urban centres experience some degree of harmful air pollution (MoE 2015). In British Columbia (B.C., the western-most province in Canada), over the past 25 years, industrial emissions have been the focus of air quality monitoring, management and policy. This focus has recently expanded to include non-industrial sources, comprising various types of emissions from urban centres. In certain regions of the province, air pollution problems are further compounded by geomorphology - pockets of air pollution periodically become trapped within mountain valleys during temperature inversions (Levelton Consultants Ltd. 2009).

The Sea-to-Sky Airshed exhibits each of these characteristics: industry, urban emissions, environmental conditions conducive to the accumulation of pollution, and an established network for monitoring pollutants. Located just north of Vancouver, B.C., the Sea-to-Sky Airshed encompasses an area stretching from North Vancouver, past the Resort Municipality of Whistler and up to Pemberton. Not only does this area contain numerous communities that have experienced air pollution levels exceeding federal and provincial air quality objectives in the past, but over the last 15 years, highway expansion and population growth, have impacted air quality. Preserving clean air quality in the Sea-to-Sky airshed is of utmost importance for health reasons and also since many communities rely on income from outdoor tourism (Meyn 2004). Due to the economic importance of the outdoor tourism industry, there is in fact greater pressure to ensure that air quality is kept pristine.

## 1.1 Problem Definition

Despite the importance of preserving pristine air quality in the Sea-to-Sky Airshed and the existence of a monitoring network, there have been no recent air pollution studies to inform air quality management and drive policy. According to the Provincial Government's air quality reporting database (found at [http://www.bcairquality.ca/reports/all\\_reports.html](http://www.bcairquality.ca/reports/all_reports.html), and verified by Graham Veale via personal correspondence on February 5<sup>th</sup> 2015) to date, reporting consists of:

- A 1995 emissions inventory (Pitre 2002)
- A summary of ambient air quality between 1984 and 2001 (Meyn 2004)
- A 2007 Air Quality Management Plan (AQMP) (Hallsworth et al. 2007)
- A  $PM_{10}$  and  $O_3$  ambient air quality summary report for Whistler, a city within the airshed (Meyn and Shead 2002)
- A 2014 Sea-to-Sky air quality management plan review (Zirnhelt and Rankin 2014)

Of these documents, the inventory and summary are the only documents that study airshed-wide air quality. The summary offers an overview of the airshed's meteorology and pollutant trends between 1984 and 2001 while the emission inventory defines the sources of air pollution in 1995. When one compares the last year of data studied (2001) to reporting in the province's other airsheds, the Sea-to-Sky Airshed is the most out of date (as listed on the BC Air Quality website: <http://www.bcairquality.ca/airsheds/bc-airsheds.html>).

This means that the airshed's monitoring network has been operating on an increasingly parallel track to management and policy efforts. Indeed, the 2014 review of the airshed's AQMP calls for an updated analysis of air quality and lists changes in air quality trends since the AQMP's implementation as the first performance indicator (Zirnhelt and Rankin 2014). The lack of airshed analysis and interpretation means that airshed management and policy lacks comprehensive information about the key pollutant trends and characteristics. As a result: efforts cannot be focused on airshed hotspots; there cannot be a data based evaluation of management and policy actions; management and policy cannot adapt to optimize efficiency and effectiveness. These consequences have particular impact since the airshed faces limited management and policy resources (G. Veale, personal communication March 19<sup>th</sup> 2015). In fact, according to Graham Veale<sup>1</sup>, the Ministry of Environment's technical

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<sup>1</sup> The British Columbia Ministry of Environment's technical advisor who oversees the Sea-to-Sky Airshed

advisor who oversees the airshed, both an airshed summary and an emissions inventory have been planned for the airshed for some time (G. Veale, personal communication August 22<sup>nd</sup> 2014). However, a lack of personnel, resources and other higher priority or time-sensitive tasks have relegated the summary and inventory to the sidelines. That the airshed's air quality is generally assumed to be good, which has done little to prioritize a comprehensive study of contaminants, and indeed has led to numerous deferrals.

## 1.2 Research Questions

In the Sea-to-Sky Airshed, there exists the need for bridging the divide between monitoring, management and policy in order to focus resources and enhance effectiveness. The aim of this thesis is to provide such a connection by analysing data collected by the airshed's monitoring network and interpreting it into guidance for airshed managers and policy makers.

Before working towards fulfilling the aim of this thesis, an initial task must be completed: since air quality data has not been used for comprehensive analysis, it must first be determined that the data will support such an aim. As such, the initial task to be accomplished by this thesis is:

- (1) Determine whether the data collected from the Sea-to-Sky air quality monitoring network between 2002 and 2013 are usable for communicating ambient air quality trends and characteristics for air quality policy and management.*

Should the data permit such a task, the primary aim of this thesis can then be pursued. To focus such work, the following research questions were developed:

- (1) How can multiple years of continuous ambient air quality monitoring data be processed to determine key trends and characteristics?*
- (2) How can identifying key contaminant trends and characteristics improve the airshed's monitoring in a way that aids management and policy to optimize resources?*
- (3) How can the analysis findings be used to make the current management system more efficient and effective?*
- (4) How can the Sea-to-Sky Airshed's divide between monitoring, management and policy be prevented from occurring again?*

The first research question involves determining a method for processing the high volume backlog hourly pollutant readings in order to extract key trends and characteristics. The second guides the application of the key findings to improving the airshed's air quality monitoring network. The network is resource-intensive and offers potential for reduction, but since this is the foundation of informing management and policy such improvements cannot come at the cost of information quality. The third question is designed to result in study that defines recommendations for improving the airshed management system. Finally, given that this thesis has identified a divide between monitoring, management and policy in the Sea-to-Sky Airshed, efforts will be made to create suggestions for preventing future repetitions.

Ultimately, these research questions should support generalizations that support the following study purposes:

- (1) Providing up-to-date guidance for actors involved with management and policy relating to the Sea-to-Sky Airshed
- (2) Defining an approach for communicating large volumes of air quality information into a guidance for airshed management and policy
- (3) Identifying measures to help prevent future divides between airshed monitoring, management and policy

### 1.3 Limitations and Scope

This thesis uses air quality, meteorological (MET), traffic and population data primarily from the Sea-to-Sky Airshed between 2002 and 2013. Since 2001 was the last year of airshed data included in airshed studies, this thesis begins with data from 2002. 2013 marks the last year of data included because the author's analysis relies on data collected and checked for quality assurance and the quality control (QA/QC) and by the MoE and Metro Vancouver. 2014 and 2015 had not yet had QA/QC.

Only pollutants that have been measured continuously by the Ministry of Environment (MoE) and Metro Vancouver are included. These include: carbon monoxide (CO); nitric oxide (NO); nitrogen dioxide (NO<sub>2</sub>); ground level ozone (O<sub>3</sub>); fine particulate matter with a mass median diameter of less than 2.5 microns (PM<sub>2.5</sub>); inhalable particulate matter with a mass median diameter larger than 2.5 microns and less than 10 microns (PM<sub>10</sub>); sulphur dioxide (SO<sub>2</sub>); total reduced sulphur (TRS).

It is important to note that the analysis involves identifying the key trends and characteristics of pollutants. Conclusively tracing pollutant emissions to sources is beyond the scope of this thesis. A subsequent emissions inventory would contain such information.

The analysis and interpretation of the airshed's air quality is primarily for policy makers and managers, but additionally, can support informational purposes for researchers. The method developed for analyzing and interpreting the air quality data in this thesis can be adopted by other airsheds and researchers who need to process large quantities of data for pollutant trends and characteristics; however this methodology should not be used for analyzing less than 5 years of data.

### 1.4 Thesis Methodology

Thesis work took place in Vancouver Canada, at the residence of the author's family. This location facilitated weekly visits with the MoE's air quality specialist for the airshed and several visits to the airshed. The author had also lived within the airshed between 2008 and 2012 and thus had an existing network of contacts and previous knowledge about the airshed. Additional contacts were established almost a year prior to submitting the thesis-- enabling the author to further develop knowledge about the area's research gap, monitoring, management, policy, and key actors. These factors created the time and working efficiency necessary to undertake the thesis aims, research questions and study purposes.

In order to pursue the thesis aim the following steps were taken:

1. Performing a literature review to determine whether methods for analyzing and communicating large volumes of air quality data existed.
2. Creating a method for analysing and interpreting data

3. Collecting data
4. Analyzing data
5. Interpreting data

Each step is elaborated in the subsections below.

### **1.4.1 Literature Analysis Method**

Initially, a survey of the CEU and Lund academic search engines and Google Scholar was completed to locate academic literature about frameworks, methodologies, or guidelines for interpreting large volume air quality data for managers or policy makers. Over 12 government databases were also surveyed in an attempt to locate reporting guidelines. Given the paucity of material, the research scope was shifted to include governmental and air quality governing bodies' air quality reports. Nine air quality reports were chosen to compare and contrast their reporting methods and report content with the previous Sea-to-Sky air quality summary in order to inform the new analysis of air quality in the airshed. Since the new Sea-to-Sky ambient air quality analysis requires the assimilation and communication of thirteen years of data for multiple pollutants as well as MET conditions, three criteria were established to select reports:

1. Reports that cover key pollutants for at least one year of data
2. Reports that investigate at least one pollutant in depth for at least five years
3. Selecting the most recent report that best conforms to criteria 1 and 2

These criteria were chosen because reports covering too little data have different structures and content due to their in-depth focus. Reports covering larger geographical areas (such as provincial scale reporting) were included if they conformed to the three criteria because these reports could contain useful lessons for reporting even larger amounts of data. Further, these reports may be privy to greater resources that could support new or at least more comprehensive reporting. The third criterion prevents the inclusion of outdated reporting approaches.

Since air quality management plans for airsheds within B.C. are based on provincial guidelines, airshed management practices have many similarities. It was assumed that this could lead to similarities between reporting approaches. As such, in an effort to ensure a wider variety of methods and content, the analysis includes reports from outside the province.

### **1.4.2 Developing the Method for Analyzing and Interpreting Air Quality Data for Policy and Management**

Since the literature analysis revealed little guidance for communicating large volumes of air quality data, the author chose to develop a method. The literature review established an overview of typically performed data analysis operations and their visual presentation. Additionally, data analysis techniques were discussed with Tamara Trafton and Rich Wildman—both tutors (professors) at Quest University Canada. Rich Wildman was a postdoc fellow in the Harvard University Center for the Environment, and has a background in physical sciences (analyzing water quality in particular). As air quality and water quality data both contain large amounts of seasonal time series data with impacts occurring on short and long term time scales, many data analysis techniques are transferrable.

Upon summarizing the data characteristics and analysis aims to Rich Wildman, he advised four key operations: a plot of the data availability of each station's monitor, boxplots, histograms, seasonal-trend decomposition process Loess time series decomposition by Loess (STL) and autocorrelation (ACF). Boxplots are important to study whether and how typical ranges in pollutant levels vary across the airshed. Autocorrelation offers information about persistence (how much data affect subsequent measurements) as well as preliminary indications about day, week and seasonal variations (R Wildman, personal communication March 3<sup>rd</sup> 2015). The seasonal-trend decomposition procedure based on Loess (STL), can communicate the relative significance of different pollution patterns (R Wildman, personal communication March 3<sup>rd</sup> 2015). Such information can identify the patterns that most effect pollutant levels.

He also advised the use of R analytical software to save time and preserve data quality. The author learned to use 'R' through over two weeks of studying online tutorials and reading the 'R' user manual. Connor Mcknee, an undergraduate student at Quest University Canada also provided a tutorial on March 6<sup>th</sup> 2015. While learning the software, the author located OpenAir, a specialized 'R' package for analyzing air pollution. The author learned how to use this package by reading the user manual. The manual contains sample code which illustrates each of its various operations. This can be run with preloaded data. In order to learn the package's capabilities, the author ran and visually recorded each line of sample code.

This investigation revealed capabilities for analyzing and communicating air quality information that were not observed in the reports surveyed in the literature review. In order to select which R operations to use in the analysis, the author created the following criteria:

1. Visual representations must communicate a large amount of or significantly important analysis
2. Choices should repeat the same type of operation unless there is a need to verify the analysis with a different method
3. Choices should enable the most comprehensive and varied analysis with the fewest operations
4. Representations which can be understood by the public

This resulted in a shortlist of R operations. After consulting with Graham Veale and further reflection, the following functions were selected: `summaryPlot()`, `trendLevel()`, `windrose()`, `smoothTrend()`, `polarPlot()`, and `timeVariation()` (G. Veale, personal communication February 19<sup>th</sup> 2015).

Percentile plots<sup>2</sup> were selected because they can track high, mid and low level readings for changes across years, thereby identifying long term changes hidden during other steps in the analysis. 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles were selected to show such trends. Time variation plots were also chosen because they present seasonal, weekly and diurnal patterns. The study of average hourly concentrations plots facilitate finer scale observations such as pollution events from forest fires. Finally, pollution roses to show the movements of pollutants around the monitoring stations. The literature review identified these as another frequently seen plot in reports.

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<sup>2</sup> A percentile is a value from a set of ordered data that marks a given percentage. For instance, the 95<sup>th</sup> percentile is the value below which 95% of data, from a set ordered from smallest to largest, falls beneath.

### **1.4.3 Data Collection**

Establishing background about the airshed was first required to contextualize air pollution trends and characteristics. This consisted of gathering information for the airshed's geography, management system, monitoring network, population, traffic and MET characteristics. Most information could be acquired through research except for airshed population trends, traffic patterns and recent MET characteristics. Consequently, the author gathered and analyzed data to establish these latter characteristics.

Data for population was retrieved from BC Stats 2014. For traffic patterns, two traffic stations were chosen: Cheekye and Wedgemount. Data was retrieved from BC Ministry of Transportation and Infrastructure 2015 and BC Ministry of Transportation and Infrastructure 2015c. The Cheekye station was selected since it is located between Squamish and Whistler while Wedgemount was just north of Whistler. These choices enabled estimation of tourism traffic to Whistler. Since measurement commenced in 2005, data were downloaded from 2005 to 2013. MET information was measured at the Squamish, Horseshoe Bay and Langdale air quality monitoring stations and were retrieved from the BC Envista Database (Ministry of Environment 2015c). Vector wind directions were selected because they display wind direction more accurately than scalar measurements (G. Veale, personal communication February 5<sup>th</sup> 2015).

The air quality analysis required air pollutant data. Data from 87 monitors was downloaded, although many monitors lacked readings since they were no longer in service. Only operational analyzers were studied and these were found at the Langdale, Horseshoe Bay, Squamish, Whistler Meadow Park and Whistler Function Junction monitoring stations. Data downloaded for the analysis begins at January 1<sup>st</sup>, 2002 at 1 am, and ends at December 31<sup>st</sup>, 2013 at midnight. Due to the database restriction that prevents downloading more than two years of data, only one year of data was downloaded at a time. Data were downloaded as average hourly readings. Data were downloaded as Excel files, with original copies of the downloaded preserved. Additional files were created for data analysis.

Primary information was also gained through an airshed tour and meetings with various actors. The airshed tour took place on March 4<sup>th</sup>, 2015. Lorne Nicklason, the airshed's technician who services the stations each week accompanied the author to the Squamish, Whistler, Pemberton and Horseshoe Bay stations. Information was recorded about the type of each station analyzer, how each collects measurements and its calibration procedure. Data transferal and handling were also explained. The notes from this visit ultimately enhanced knowledge about the stations and informed the method, analysis and recommendations.

Weekly meetings between the author and Graham Veale occurred between February and April 2015. Between each meeting the author compiled a list of questions that arose while working. A meeting on March 3<sup>rd</sup> with Rich Wildman was also conducted to receive statistical guidance for creating the method. A week later, the author met with Connor McKnee for a tutorial on using 'R' software for analysis. The author also attended the SSCAS's annual general meeting on May 9<sup>th</sup> 2015. The SSCAS is a charitable society that undertakes actions for preserving clean air quality. The author attended the meeting to gain insight about the organization's structure and current progress.

### **1.4.4 Data Analysis**

For establishing the airshed background, the author calculated the average population growth for Squamish, Whistler, unincorporated areas within the Squamish-Lillooet region, Gibsons, Bowen Island, Pemberton, and Lions Bay between 2002 and 2013. This was compared to the province wide percent change in population (also calculated by the author). To determine weekday and monthly traffic patterns, the author created time series plots of the monthly averages of each weekday for 2005, 2009 and 2013 at the Wedgemount and Cheekye stations. Average annual weekday traffic between 2005 and 2013 was also plotted to identify long term changes.

To describe MET conditions, station summaries were first created to map data availability. These can be found in the appendix, plate D, object D-1 to D-3. Mean, min, max, boxplots and histograms were then used to check the range and distribution of data for anomalies. A number of significant errors were identified and removed. After, temperature and humidity readings were graphed for each station using a time series plot of mean monthly readings and a plot for mean diurnal readings. The author chose this format so that seasonal and daily variations would be displayed. Wind roses, a common tool used in reporting (identified by the literature analysis), were used to display the distribution and direction of wind speeds at each station. Annual, monthly and daytime versus night time roses were made to communicate seasonal and daily wind patterns.

Temperature and wind roses were compared to the MET review in Meyn's Sea-to-Sky Ambient Air Quality Summary (2004). Inaccurate wind direction readings were identified between 2001 until May 2015 at the Squamish station. This resulted in the removal of all Squamish wind direction data from the summary.

For the analysis of air quality data, data were first visually inspected and unknown data categories such as 'sigma all', and 'uvec' were clarified by Graham Veale (G. Veale, personal communication February 5<sup>th</sup> 2015). Data were then checked using the same process as for the MET readings. Missing Horseshoe Bay readings were identified, and Graham Veale supplied the missing readings (G. Veale personal correspondence March 28<sup>th</sup>).

The next step was to create a table to visually plot the functional analyzers by station, and to indicate the annual percentage of data that was recorded. This is important because according to the BC government air quality objectives guidelines, data must be at least 75% complete in order to assess ambient air quality standards (MoE 2011). Canadian and British Columbian air quality objectives were then calculated according to these requirements outlined.

After, all measurements on February 29<sup>th</sup> 2004, 2008 and 2012 were deleted to simplify data handling. Data then converted to a format compatible with 'R' and the various analytical operations were completed. For reference, the code used to perform each operation can be found in the appendix, plate A.

## 1.5 Disposition

Not merely can it be said that without monitoring there is no management, but rather, that monitoring and management will occur in parallel unless analysis and interpretation bridges this divide. This has been the case for at least 10 years at the Sea-to-Sky Airshed. The aim of this thesis is to provide such a connection by analysing data collected by the airshed's monitoring network and interpreting it into guidance for airshed managers and policy makers. The literature analysis, found in the next chapter, lays the foundation for fulfilling this aim and research question 1: *how can we process multiple years of continuous ambient air quality monitoring data to*

*determine key trends and characteristics.* The analysis will explore methods of approaching and communicating data that is similar to what will be used in this thesis. After a survey of academic literature, the analysis uses the 2004 Sea-to-Sky Ambient Air Quality Monitoring Report as a basis of comparison against other similar reports. Ultimately, the similarities and differences between it and other reports guides the development of the method for analysis and interpretation used by this thesis. We then turn to establishing foundational knowledge about the managerial and political framework that the airshed is embedded within (chapter 3). Chapter 4 provides an overview of the key attributes of the Sea-to-Sky airshed, specifically: geography, station network, population, point sources, mobile sources, and MET background. This chapter provides context for chapter 5, the Ambient Air Quality Analysis. The analysis applies the method developed for research question 1 in order to identify the ambient air quality trends and characteristics for each pollutant monitored at each station across the airshed. The discussion (chapter 6) reflects on the method, and uses a criteria for filtering the ambient air quality findings into key findings. Here we can also find a discussion of which characteristics and trends are of significance and their management priority. The discussion also raises some areas of time and resource savings that were discovered during the process of analyzing and interpreting the findings. The conclusion (chapter 7) outlines significant data quality improvements identified by the thesis methodology, concisely presents the methodology and its application, and further interprets the results of the analysis into a table for guiding airshed management and policy. Two sets of recommendations connect the findings to monitoring and management improvements (question 2 and 3 respectively). Final reflections about preventing future disconnect between the airshed's monitoring and management (research question 4) complete the thesis.

## **2 Literature Analysis**

The following literature review examines existing air quality reporting in academic literature, and actual air quality summaries throughout North America and Europe. The analysis aims to form a foundational knowledge about the approach and methods of presentation used in existing air quality analyses—particularly ones which study multiple pollutants over a period longer than two years. In turn, this knowledge informs the method of analysis and interpretation used for this thesis. The literature analysis contains two parts, one: which surveys existing academic literature regarding the design of air reports and analysis, and two: a review of ten air quality summaries. The 2004 Sea-to-Sky Ambient Air Quality Monitoring Report merits close inspection since it most resembles the analysis and interpretation performed in this thesis. Both the thesis and the report summarize a many years of data for multiple contaminants, and moreover, they are both of the same geographical area using the same monitoring network. Reports from North America and Europe are also studied, and these together with the 2004 Sea-to-Sky report are compared and contrasted to determine common and novel approaches and methods for communicating air quality data.

### **2.1 Academic Literature on Air Quality Reporting**

An overview of Academic Search Complete and Google Scholar found that the majority of articles focus on informing the creation of air emissions inventories, likely because these are used more frequently than air quality summaries. Some examples include Kota et al. 2014, which evaluates the performance of two models for tracing the amount of vehicle exhaust for emission inventories. Borge et al. 2014, conducted a review of emissions source studies and connected this to the development of an emissions inventory. The identified sources were then linked to emission reduction policies and a future scenario of emission reductions. Zhou et al. 2014 present a new regression based method for calculating sources for emission inventories. Out of these three papers, Borge et al. 2014's comes closest to resembling this thesis, but linking emission inventories to policy is dissimilar to the aim of this literature analysis.

Other articles tend to offer improvements and novel approaches to modeling pollutants. Marc et al. 2015 reviews various air quality devices and sampling techniques while Gomez-Losada et al. 2014 pioneer a finite mixture model to separate stations based on their pollution levels. A GIS based assessment by Righini et al. 2014 could plan or optimize monitoring station locations based on variations in pollutant levels. Dogruparmak et al. 2014 uses principal component analysis to group monitoring stations by pollution pattern to determine whether reductions can be made to the monitoring network. A novel monitoring technique is developed by Baldauf et al. 2008 to measure pollution levels near highways.

Few articles offer specific guidance on reporting, analyzing, communicating and summarizing data for multiple pollutants over multiple years. The closest articles found are Shamsipour et al. 2014 and Kuhlbusch et al. 2013. Shamsipour et al. 2014 offers a method for detecting implausible measurements, inconsistent data and can pattern anomalies. After applying this method to a large set of PM<sub>10</sub> data in Tehran, the authors claim to have improved data quality. Kuhlbusch et al. 2013 summarizes the history of monitoring methods, suggests the integration of multiple monitoring techniques, and makes several suggestions for future monitoring techniques.

Given the lack of academic literature guiding air quality reporting, we must rely instead on recent air quality reports in North America and Europe in order to inform the design of a new method for analyzing and interpreting air quality data.

## 2.2 Analysis of Air Quality Reports from North America and Europe

The 2004 Sea-to-Sky Ambient Air Quality Monitoring Report's aim was to provide a baseline summary of ambient levels of criteria air contaminants starting from the beginning of monitoring in the region (Ministry of Water, Land & Air Protection, Lower Mainland Region 2004). The data range from 1984 to 2001 and are from a combination of eighteen continuous and non-continuous monitoring stations. The geographical range of the airshed extends in a band from Howe Sound to Pemberton, B.C. and contains several towns.

The 93 page summary report contains an executive summary and an introduction detailing the compatibility of data over the data range and the geographical aspects of the airshed. The report contains a short section describing the history of the monitoring network. A chart describes the type of pollutants measured and the duration of measurement per station. Another section provides an overview of the federal and provincial air quality objectives. MET information is described in terms of wind and temperature. After a short description of the stations, this section portrays wind data as the percentage of valid data captured, the annual average wind speed, the percentage of calm winds annually, and the frequency and direction and speed of winds (portrayed with wind roses for each season). Temperature data is presented for each sub-region and for the Squamish Western Pulp (Woodfibre) MET Station. This is measured with the annual percent data capture, annual min and max, mean and standard deviation of temperatures.

Two sections outlining monitoring results follow, one for continuous and the other for non-continuous measurements. The continuous section is the most detailed with an explanation of the pollutant characteristics (including general impacts on health and the environment), sources, air quality objectives and monitoring results for each pollutant. Each monitoring station is described and its pollutant data is summarized in terms of percent data capture, annual average, max 1-hr concentration and max 24-hr concentration. The reasons behind some of the station's pollutant levels and occasionally the number of times pollutants surpass a given concentration are also reported. Results are compared to Canada-wide, BC and Health Reference level standards. Pollution information is also described using standard deviation and occasionally maps illustrate the concentrations of pollutants for all hours over a given year. Pollutants measured by non-continuous monitors are described by characteristics, sources, air quality objectives, and monitoring results for each pollutant. The data is also split into geographical sub-regions which are described by the number of samples, the annual average, the maximum 24-hr concentration, and number of exceedances. The report finishes with references, glossary, and an appendix with station photos and descriptions, and yearly wind roses for the communities of Squamish and Langdale.

This report has helped guide the airshed's management. Specifically, the report was referenced in the airshed's 2007 AQMP (along with the 1995 Sea-to-Sky Airshed Emissions Inventory of Common Air Contaminants which aimed at guiding actors and actions to "ensure clean air throughout the Sea-to-Sky Airshed" (Hallsworth et al. 2007). Given that the AQMP was reviewed in 2014 (Zirnhelt and Rankin 2014), it appears to have formed the cornerstone of the airshed's management to date.

Table 2-1 outlines the reports that were compared to the old Sea-to-Sky report. For each report listed below, a separate table has been created that enumerates the similarities and differences between it and the Sea-to-Sky report. These tables can be found in the appendix, plate A.

*Table 2-1 Description of reported airshed and rationale behind report selections*

| <b>Report</b>  | <b>Characteristics</b>  |
|--|---|
| Williams Lake Airshed Management Planning Background Air Quality Report (for Data Collected 1990-2002); B.C. | Small airshed population (25,122 people). Airshed located in the northern interior of BC. Report selected as it is the most recent report of similar content for the airshed. Report was conducted to ascertain air quality and to inform management.   |
| 2011 Lower Fraser Valley Air Quality Monitoring Report; B.C.   | This airshed contains the highest population and is the object of the most air quality studies in BC. This report was chosen since the airshed appears to have more resources than most other airsheds and since the report is one of the newest in the province. New methods may be present.   |
| Staying the Course, 2013 Annual Report; Parkland Airshed Management Zone, Alberta                            | This airshed covers an area of 42,000 square kilometers and contains more than twelve cities and towns and two large National Parks. This report marks one of the most recent airshed reports, and while it presents only data from 2013, it offers an analysis of a full range of contaminants.  |
| Saskatchewan Air Quality 2000-2009 Report  | Saskatchewan is an interior province of Canada and conducted an air quality review for province wide air pollution between 2000 and 2009.   |
| Air Quality Standards Compliance Report (AQSCR); South Coast Basin, Southern California                      | This report was selected due to the existence of Los Angeles within the air basin. Los Angeles is one of the most well studied air basins in the United States and is well known for its smog pollution events. It is assumed that management of the basin is well developed compared to other basins throughout the country. This particular report focuses on PM, CO, NO <sub>2</sub> , with limited reporting on lead, SO <sub>2</sub> and sulphates for 2005 and 2006 |
| Trends in Bay Area Ambient Particulates; California  | This basin also contains at least one large city, (in this case San Francisco). This report summarizes over twenty years of PM data and therefore could offer lessons for summarizing data over long time periods.  |
| New York City Trends in Air Pollution and its Health Consequences  | New York City started city wide monitoring of pollutants deemed important to public health in 2009. Pollutants include PM <sub>2.5</sub> , SO <sub>2</sub> and Ni. The report summarizes pollutant trends and their effects on health from the beginning of monitoring until 2013 (NYC  |

|                                   |   |
|-----------------------------------|---|
|                                   | Health 2013).   |
| Air quality in Europe—2014 report | This report summarizes air quality throughout the EU between 2002 and 2014. While part of the report evaluates progress towards directives, it is still included since it summarizes by far the most data of all the reports. Given the recent release of the report, its geographical range, and that it is written by the European Environment Agency, the report is predicted to be of high quality and to be a likely source of new approaches (European Environment Agency 2014).  |
| Malmö 2013 air study; Sweden      | Malmö is the third largest city in Sweden and has been monitoring air quality since the 1970s. Internationally, Malmö is reported to have good air quality, and has made improvements in pollutant levels throughout the city. Malmö has an excellent database of reports stretching back to 1966, with multiple reports released each year. Given the experience and resources dedicated to reporting, it was predicted that this air study would represent a high quality example of reporting. This report summarizes multiple pollutants within the city for the year 2013. |

*Source (listed in order of appearance): Schutte et al. 2003; Doerksen et al. 2013; Parkland Airshed Management Zone (PAMZ) 2013; Saskatchewan Ministry of Environment 2011; South Coast Air Quality Management District 2006; Fairley 2011; NYC Health 2013; European Environment Agency 2014; Environment Committee Miljönämnden 2013.*

## 2.3 Reflections

After reviewing the air quality studies, it becomes apparent that the Sea-to-Sky report is fairly unique in summarizing both multiple pollutants and multiple pollutants over a lengthy time period. The Sea-to-Sky report also consists of comparatively detailed reporting of numerical data, especially given the airshed’s resources. Reporting of wind, and polluted wind is the most detailed of all the reports. It is interesting to note that there were more similarities between Canadian reports and European reports as compared to Canadian and US reports, although additional European reports would need to be analyzed to determine whether this trend indeed exists.

Overall, air quality summary reports contain a number of similarities. All reports but one begin with either an executive summary or a summary and then an introductory section. Introductions tend to describe the airsheds or air basins, the management systems and their history, and also monitoring stations. Monitoring stations usually have a basic site description, and a chart containing the pollutants measured and dates of the station’s operation. There is generally no discussion of the purpose behind the assorted monitoring programs. The Lower Fraser Valley report stands as an exception since it mentions that the data are used for communicating air quality information to the public, and even specifies a type of communication tool (air quality health index values) that the data are used for. It also explains that the purpose of the monitoring network is to develop an understanding of the air quality

levels that residents experience. Reports also differ in the level of analysis and the amount that is communicated. Critical information appears to be annual pollutant characteristics, pollutant averages, a discussion and/or illustration comparing the pollution levels to existing standards and an explanation of pollutant sources. Given that the above items are almost always, or always found, one could consider such content as critical content. Sticking to this content would offer a basic summary.

To inform the design of a more comprehensive analysis and interpretation, we must now look at key additions observed in the reports. While some variation in the report can be attributed to different reporting aims and study periods, these differences do illustrate alternative options for analyzing and presenting data.

- PM, O<sub>3</sub>, NO<sub>x</sub> and SO<sub>x</sub> were the key pollutants included in reports, reflecting their important influence on concerns such as human and ecological health. Variable pollutants were volatile organic compounds, total reduced sulphur, benzene, airborne metals, carbon, methane, ammonia, polycyclic aromatic compounds, and hydrocarbons. Reporting of these variable compounds appeared to depend upon whether significant concentrations exist, the airshed priority, and airshed resources, and existing air quality objectives and standards.
- The Bay Area particulate report presented the most statistically detailed information. The methods used for describing data uncertainty and making correlations could enhance the quality of future air quality analyses.
- Percentiles that were chosen varied between reports, but unfortunately the rationale behind choosing the percentiles was not included. From the nature of their use in the reports, percentiles appeared to be used for filtering extremes in the air quality data or to present and analyze data in for air quality objectives. That being said, scientific reports such as Shamsipour et al. 2014, and the Bay Area particulate report offer additional data filtering techniques.
- Including outreach content could enhance the public accessibility of the report. This could resemble engagement through organizing photo contests where winners have their photos published within the report, and also by including a section detailing suggestions for public involvement (exemplified by the Parkland Airshed Management Zone report).
- While greenhouse gases (GHGs) were only included in the European summary reports, including such an analysis could set a rare example of reporting in North America.
- The Malmo report illustrates urban pollution in a highly visually appealing manner by mapping the concentrations of one pollutant throughout the city using a resolution of 1 meter squared. While some airsheds may not have such high resolution data, lower resolution maps could still be made using air dispersion models. Further, highlighting streets according to their risk of exceeding standards was also an effective method of communicating exposure risks.

- Offering a section that compares air quality results to other airsheds, especially those of similar characteristics contextualizes the report findings.
- In terms of communicating exceedances and pollution episodes, South Coast offers accessible graphs illustrating the number of annual exceedances. This enables readers to gain a snapshot of information and to help visualize longer trends. On the other hand, the EU report offers a description of the characteristics and causes of high PM pollution episodes in France and the UK in 2014. Communicating such information could also be possible, especially for less polluted airsheds with few exceedances.
- The Williams Lake and Lower Fraser Valley reports discuss and graph seasonal and diurnal trends quite effectively. These analyses are important since they illustrate the wide variation in pollution each day and month and can offer indications about emissions sources.
- The inclusion of an analysis of vehicles and emissions in the EU report was unique from the other reports that were surveyed. Conducting such an analysis could be vital for airsheds that have undergone significant changes in transport.
- Finally, including a summary and recommendations at the end of the report improves the ease of understanding the key findings. The past Sea-to-Sky summary does not have such sections, and this impacts the reader's ability to comprehend the findings that are dispersed throughout the report.

The first part of the literature analysis revealed that very few articles in academic literature offer guidance for the reporting of large air quality datasets, nor about air quality reporting practices. According to the second part of the literature analysis, we can observe that the Sea-to-Sky report is a fairly unique in summarizing such a long period of a significant number of pollutants. We can also see that there appears to be a set of components that are found across almost all to all of the reports surveyed. We can consider these as basic components. The literature analysis also identified a set of less common components which offer potential for enriching a basic air quality summary.

### 3 Introduction to Airshed Monitoring and Management

The airshed and air basin approach to monitoring and management is relatively recent. It was only after the London Smog events (leading up to and including the event in 1952) that the health impacts of air quality, and air quality gained prominence (Kuhlbusch et al. 2013). Air quality management is generally organized by making geographical divisions of a region, with management being the responsibility of either governments and/or organizations (Pope and Wu 2014). These management regions are restricted to the lower atmosphere, and are divided into areas within which air emissions are homogeneously transported and dispersed (Schutte et al. 2003). Topography (particularly mountain ridges and valleys) typically determines boundaries, while flatter regions are instead delineated by geographical coordinates or municipal, county or township boundaries. According to the Canada-wide Air Quality Management System (AQMS)<sup>3</sup> currently implemented through the Canadian Council of Ministers of the Environment (CCME) (CCME 2014), these areas are referred to as both 'regional airsheds' and sub-regional 'air zones.' Alternatively, Alberta uses the term 'airshed zone' (PAMZ 2013). In the US, such regions are often referred to as air basins (Bloemhard 2002; South Coast Air Quality Management District 2006).

The management body oversees a network of air quality monitoring stations strategically situated around the airspace (Pope and Wu 2014). These monitoring stations contain equipment for monitoring contaminants. In the first half of the 20<sup>th</sup> century, measurement methods were typically labour intensive, required significant time to process and therefore could not offer frequent readings (Kuhlbusch 2014). In the latter half of the century, improved techniques and equipment expanded monitoring techniques which enabled detection of lower concentrations of contaminants with automatic continuous<sup>4</sup> readings (Kuhlbusch 2014).

The monitoring stations record ambient (levels of dispersed pollutants) concentrations of pollutants. In Canada, some measured contaminants are: ground level ozone (O<sub>3</sub>), nitrous oxides (NO<sub>x</sub>) sulphuric compounds (SO<sub>x</sub>), and particulate matter<sup>5</sup>. In Canada, many of these pollutants fall under the category of Common Air Contaminants (CACs) and in the US a largely similar list of pollutants is referred to as Criteria Pollutants (Schutte et al. 2003; South Coast Air Quality Management District, 2006).

According to Marc et al. 2014, the central purpose of air quality analysis and monitoring is to create reliable analytical information to support various processes. These processes include: identifying pollution sources, determining range of the pollutant's influence, assessing environmental impacts of the pollutants, and assessing the impact of policies and regulations. In Canada, a suite of objectives provide benchmarks for evaluating such processes—especially when they relate to public health. Objectives can be set federally, provincially, municipally or by airshed management bodies—provided that they are stricter than existing objectives set by the levels holding higher authority (Doerkson 2013, MoE 2014b). In other words, the BC provincial government can only set objectives that are stricter than the federal government.

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<sup>3</sup> This applies to all provinces except Québec.

<sup>4</sup> Continuous, as in measured recorded on an ongoing basis as opposed to periodically

<sup>5</sup> PM is typically divided in PM<sub>10</sub> and 2.5 based on size, but for the purposes of the analysis will be grouped together unless otherwise indicated.

From the reports reviewed for the literature review, we can see that management bodies tend to release reports that assess the processes and objectives outlined above, although the period of data analyzed and the frequency of such reports varies significantly. Many will also supplement the summaries with reports on specific pollutants, and with reports on trial monitoring and modeling systems.

### 3.1 Airshed Management in British Columbia

Within B.C.<sup>6</sup>, managing air quality using airsheds was only developed during the mid-1990s (Schutte et al. 2003). According to this source and the 2009 review of airshed planning in B.C. (Levelton Consultants Ltd. 2009), pre-1990 airshed management in B.C. consisted of monitoring and restricting industrial point source emissions. However, as these emissions decreased, and as non-point sources of emissions (such as emissions from heating, cooking and transport) increased, emissions from diffuse urban sources came to the forefront. Vehicle emissions became the primary urban source.

In the early 1990s, the Environmental Management Act (formerly the Waste Management Act) was revised to enable the regulation of emissions of area and non-point sources like open burning, vehicular emissions and fuel quality (Schutte et al. 2003, Levelton Consultants Ltd. 2009). This point marked the start of air quality improvement and education programs like ‘Clean Air Day’ and the ‘Wood Stove Exchange Program.’ Regions across the province also began to devise air quality management plans (AQMPs). The Smithers Airshed was the first to adopt such a plan in 1992, and this was followed by others such as Metro Vancouver’s (formerly GVRD) first plan in 1994, and finally the Sea-to-Sky Airshed’s Sea to Sky Air Quality Management Plan in 2007<sup>7</sup>.

AQMPs operate with a variety of actors working in tandem. Traditionally, the MoE regulates emissions by issuing permits, and holds responsibility for monitoring and reporting ambient air quality (Hallsworth et al. 2007). This can be effective for regulating point sources such as industries. Municipalities can set bylaws to manage items such as idling and open-burning. AQMPs are developed to meet the need for managing mobile and area sources and to provide a medium for the multitude of provincial and regional stakeholders to cooperate.

### 3.2 Monitoring and Management in the Sea-to-Sky Airshed

The Sea-to-Sky Airshed is managed and monitored by a number of different bodies. Large stationary emissions sources are regulated by the MoE since this body permits such sources. Regional districts and municipalities manage airshed emissions through bylaws, should they so choose. In the past, bylaws for backyard burning, anti-idling, and wood-burning appliances have been instated in some of the regions (Alderson 2007). Since 2002, an ad-hoc committee called the Air Quality Coordinating Committee (AQCC) has helped to manage the airshed and coordinate between stakeholders (Sea-to-Sky Clean Air Society 2015). This committee was later restructured and renamed the Sea-to-Sky Clean Air Society (SSCAS) (Zirnhelt and

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<sup>6</sup> The province within which the Sea-to-Sky airshed is located.

<sup>7</sup> Although the Air Management Coordinating Committee was formed in 2002.

Rankin 2014). The SSCAS now organizes and participates in projects, educates the public and conducts research about air quality (Sea-to-Sky Clean Air Society 2015b).

The airshed's AQMP (released in 2007), was developed collaboratively by the AQCC, which at the time consisted of representatives from municipalities, regional governments, the MoE and local industries, transit companies and utility companies (Hallsworth et al. 2007). The AQMP represents a regional, collaborative plan for ensuring clean air quality in the Sea-to-Sky Airshed and provides a method to address non-permitted emissions sources like transportation, electricity use and agriculture (Hallsworth et al. 2007). The plan was made actionable for the SSCAS through an implementation framework developed in 2008 (Sheltair Group 2008). According to the 2014 review of the AQMP, 13 out of 18 actions that it specified have been implemented, but implementation has been impacted from insecure funding and loss of connection with local governments. As mentioned in the problem definition, the AQMP was developed based on scientific study using air quality data up to 2001. As time passed, airshed management and airshed monitoring increasingly operated as parallel processes.

Air Quality monitoring within the Sea-to-Sky Airshed began in 1971 due to concerns about mercury emissions from a chlor-alkali plant based in Squamish (Meyn 2004). A program arising from the 1971 Pollution Control Act also helped spur initial monitoring. This early monitoring program consisted of monitoring total suspended particulate (dust), coefficient of haze and sulfation plate measurements. In 1984, Squamish became the site of the first modern ambient air station, and has operated to this day.

During the author's tour of the Sea-to-Sky monitoring network on March 4<sup>th</sup> 2015, it was determined that the present monitoring network consists of 8 stations that contain analyzers for contaminants, MET data or both. Most stations have continuous analyzers, except for Pemberton which does so non-continuously and the mobile Whistler Function Junction station which only collected 2 months of measurements around the 2010 Vancouver Winter Olympics. Stations are mainly administered by the MoE, and the airshed's southernmost station (Horseshoe Bay station) is the responsibility of Metro Vancouver. The Langdale and Port Mellon MET stations are administered by Howe Sound Pulp and Paper. The stations are located on top of buildings or as independently standing stations. At times, the National Air Pollution Surveillance program (NAPS) supplies capital operating equipment and cover laboratory costs for the stations (G. Veale, personal communication February 19<sup>th</sup> 2015).

The analyzers at each station measure the data which is then collected in the station's data logging system before being automatically uploaded to the publically available BC Envista Air database. At this point, some of the data are used for calculating the real-time, publically available Air Quality Health Index that is displayed on the BC government website: <http://www.bcairquality.ca/readings/>. Every year, the past year of data undergoes a QA/QC process (G. Veale, personal correspondence March 19<sup>th</sup> 2015). After these actions are complete, data languishes on the BC Envista Air Database.

## 4 Background on the Sea-to-Sky Airshed

Defining the geographic boundaries of the Sea-to-Sky Airshed has been an iterative process stretching over a decade. The earliest published definition of the airshed boundaries is found in the first airshed inventory report, released in 2002 (Pitre 2002). The same map is used for the ambient air quality summary released in 2004 (Meyn 2004). It was only the 2008 Sea-to-Sky Clean Air Society's annual report that the next airshed map can be observed (Sheltair Group 2008). This version is the first to show a united airshed body; previously the airshed was represented as upper and lower regions.

According to the current boundaries, the airshed encompasses a 150 kilometer long corridor stretching from the Howe Sound entrance in the Strait of Georgia to just north of the community of Pemberton. The airshed is characterized by a diverse range of altitudes, temperatures and wind patterns (figure 4-1). The bottom third of the region is dominated by ocean and islands, while the upper two thirds consists of coniferous forested mountains and glacier carved valleys. Highway 99 bisects the airshed, running in the south to north-east direction, and provides a major throughway for traffic between communities and through the region.

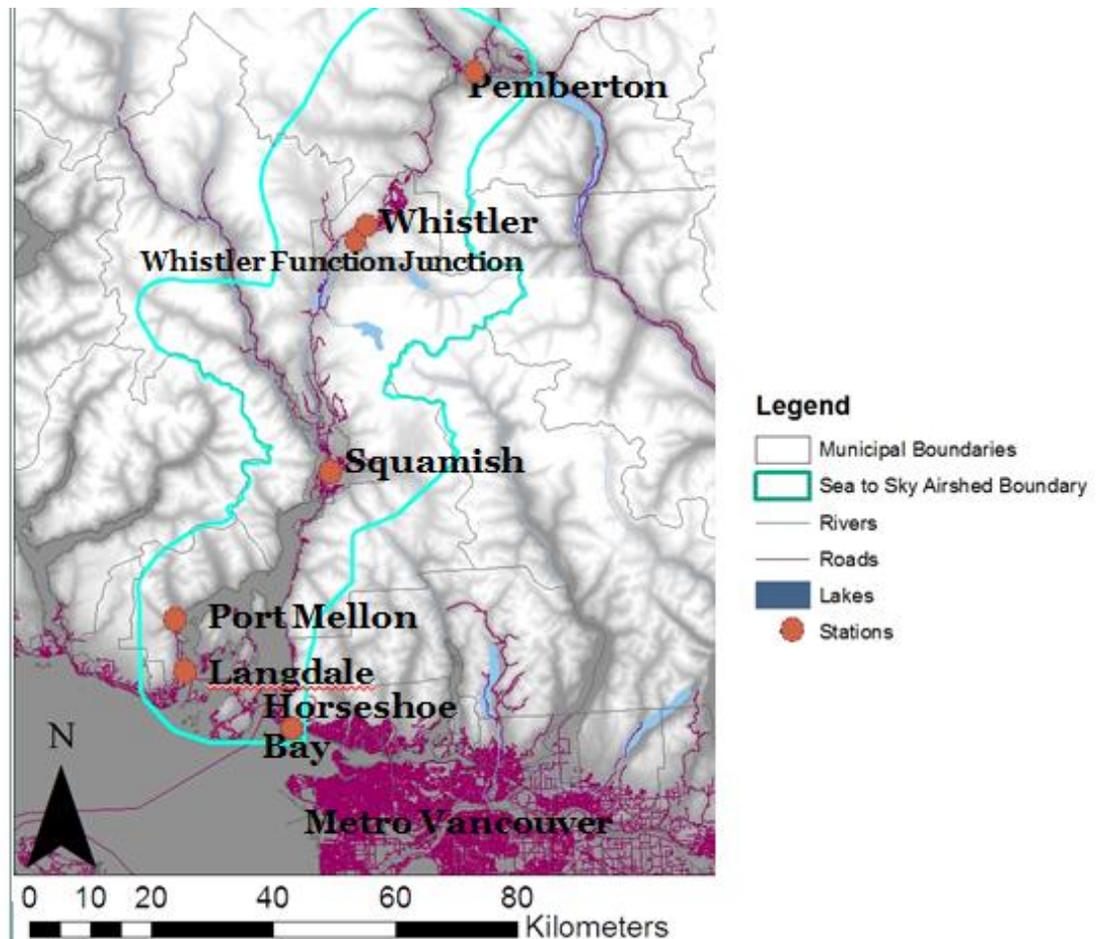


Figure 4-1 'Map of Sea-to-Sky Airshed geography and air quality monitoring network'

## 4.1 Population

In terms of airshed population, the author calculates that according to the measurements of the 2014 B.C. census, the population within the airshed consisted of 48500 people (BC Stats 2014)<sup>8</sup>. Between 2001 and 2013, the author further calculates that the population grew 17% as compared to the average 12 % growth province wide<sup>9</sup>. In other words, the airshed's increase in population has been significantly higher than the provincial rate of growth. This puts added pressure on the airshed's air quality by means such as having more cars on the road and increased utility use.

The main communities within the airshed are (listed in order of decreasing population size) Squamish, Whistler, unincorporated areas within the Squamish-Lillooet region, Gibsons, Bowen Island, Pemberton, Lions Bay and Langdale. These communities are characterized by a range of activities, tourism being the most common, especially in the airshed's north. Squamish, the largest community has been building its reputation as 'The Outdoor Recreation Capital of Canada' (Tourism Squamish 2015), with hiking, mountain biking, cross country skiing, wind surfing, rock climbing activities being some of its attractions. The Resort Municipality of Whistler is located around the foot of Blackcomb Mountain, and as such it is a year round resort destination for alpine sports, hiking and mountain biking (Tourism Whistler 2015). Blackcomb Mountain hosted some of the venues for the 2010 Winter Olympics. The town of Gibsons is an Oceanside community with a working harbour and known for its ocean, oceanside and park activities (Town of Gibsons 2014). Bowen Island is a residential community located a 15 minute ferry ride west of Horseshoe Bay. Pemberton, representing the farthest north community within the airshed gains a large part of their income through tourism jobs and is also the site of agricultural and forestry activities (Village of Pemberton 2015). Lions Bay is one of the smallest municipalities in B.C., and is mainly residential. Langdale is a village situated at the BC ferry terminal site which provides the main connection between Highway 101 (running up the Sunshine Coast) and Highway 99 (running north-south past Horseshoe Bay) (ehCanada 2015).

## 4.2 Key Point Sources

In terms of industry, the Sea-to-Sky airshed contains several pulp and paper plants. One, owned by Western Forest Products, was located to the southwest of Squamish and closed in 2006 (Woodfibre LNG 2015). The other, the Howe Sound Pulp and Paper Mill is located close to Langdale and maintains a MET station to the north – north-western side of the mill for providing wind data for monitoring the mill's emissions.

## 4.3 Key Mobile Sources

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<sup>8</sup> This estimate was calculated by the author by combining the populations of the main communities within the airshed, which are (listed in decreasing order of population size): Squamish, Whistler, unincorporated areas within the Squamish-Lillooet region, Gibsons, Bowen Island, Pemberton, and Lions Bay.

<sup>9</sup> The author calculated this estimate by adding the populations of the same communities together for 2001 and 2013 and then dividing the two outcomes.

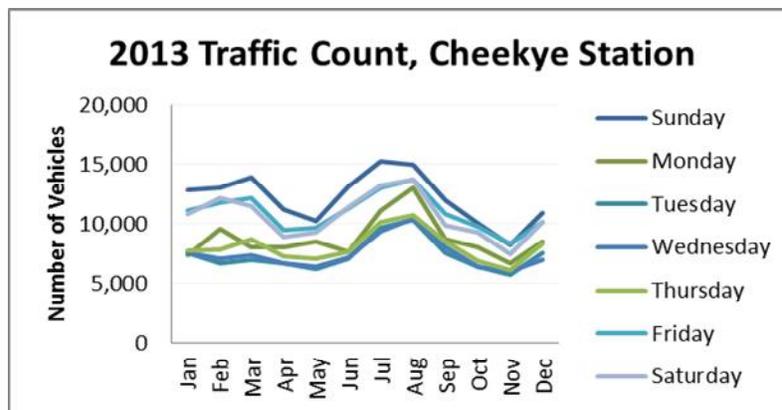
Vehicles are estimated to be one of the main sources of pollution within the airshed (Hallsworth et al. 2007). Key pollutants emitted by vehicles are: NO<sub>x</sub>, volatile organic compounds, CO, and fine particulate matter (Ministry of Environment 2015b). These can also react to form ground level ozone. The significance and impact of these contaminants shall be explained in the second section of the next chapter.

Not only are there emissions from local traffic within the communities, but they also arise from the Sea-to-Sky Highway which bisects the airshed in the north-south direction. This creates a corridor between communities and also provides a route for traffic to enter and exit the airshed. Of particular importance is the commuter traffic between the communities (especially in the south) to Metro Vancouver and tourist traffic between Metro Vancouver and the northern communities (primarily Whistler and Squamish).

As mentioned in the section 1.4.3, two traffic counting stations were selected to estimate the highway traffic—especially that arising from Whistler’s tourism. These stations are located in Cheekye (approximately 10 km north of Squamish) and Wedgemount (5.8 km north of Alpine Way, Whistler). Between 2005<sup>10</sup> and 2013, traffic passing the Cheekye station is almost three times higher than at the Wedgemount station. This is most likely because the Cheekye station measures tourism traffic in addition to highway traffic passing between communities. The Wedgemount station, on the other hand, is located just north of Whistler, the airshed’s primary tourism attraction. Remaining traffic is most likely for local movement for the community of Pemberton and vehicles traveling to and from destinations north of the airshed. From these observations, tourism at Whistler appears to contribute significant traffic emissions to the airshed.

Friday, Saturday and Sunday traffic volume remained consistently higher at the Cheekye station (figure 4-2 and 4-3). At Wedgemount, Friday was the heaviest day while Sunday was generally the lowest traffic day—although the volume for all days was much more even compared to at Cheekye. This pattern again points to higher traffic from tourism activities in Whistler.

Interestingly, monthly traffic counts are higher during the summer than winter, with the second highest period being early spring. This defies the author’s expectation that Whistler’s ample winter attractions would create a winter peak in traffic (that being said Whistler has been designed as an all-season resort). At the Wedgemount station, traffic also peaks in July and August, however, there is no secondary early spring peak.



<sup>10</sup> There was no earlier data available at both sites

Figure 4-2 'Average daily traffic, separated by month at the Squamish Cheekye traffic counting station: 2013'

Data Source: 'BC Ministry of Transportation and Infrastructure 2015'

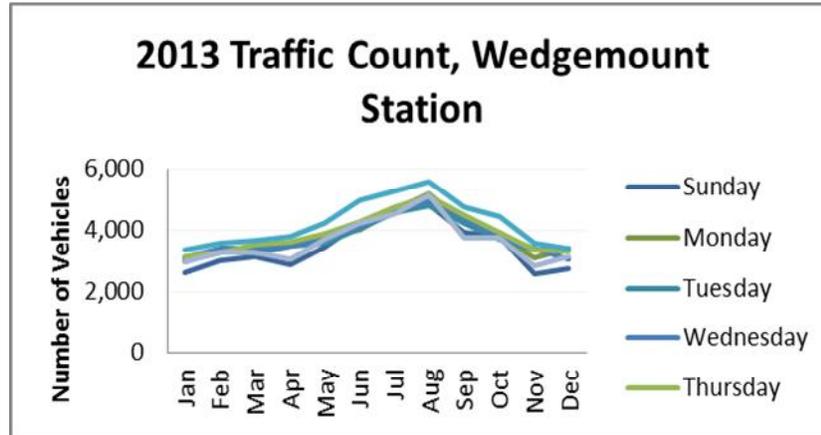


Figure 4-3 'Average daily traffic, separated by month at the Wedgemount traffic counting station: 2013'

Data Source: 'BC Ministry of Transportation and Infrastructure 2015b'

While traffic variation is highest seasonally, there appears to also be a small average annual growth in traffic counted at Cheekye (figure 4-4). This translates into an additional 1000 to 3000 vehicles on the road each day of the week between 2005 and 2013. More vehicles were added on peak days of the week (Friday, Saturday and Sunday) which exerts further pressure on air quality. On the other hand, the Wedgemount station shows negligible long term change. The biggest change was a gain of 500 vehicles or less between 2006 and 2009 and a loss of a roughly equivalent amount between 2009 and 2011 (figure 4-5)

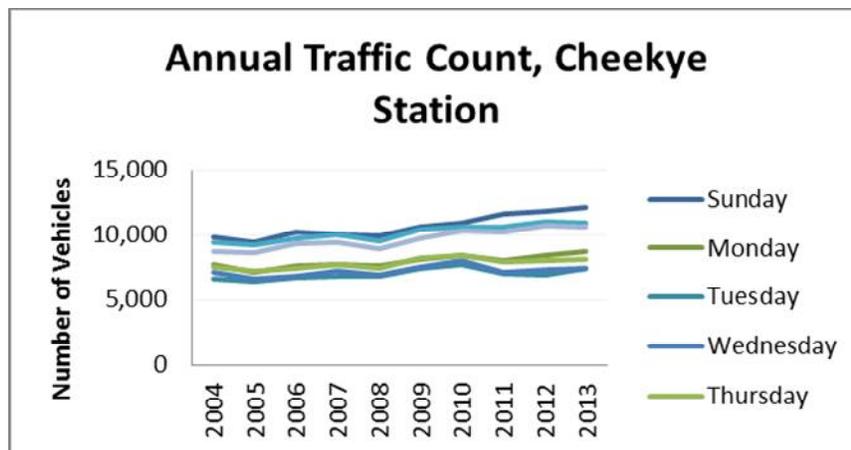


Figure 4-4 'Annual average daily traffic for each day at the Cheekye traffic counting station'

Data Source: 'BC Ministry of Transportation and Infrastructure 2015'

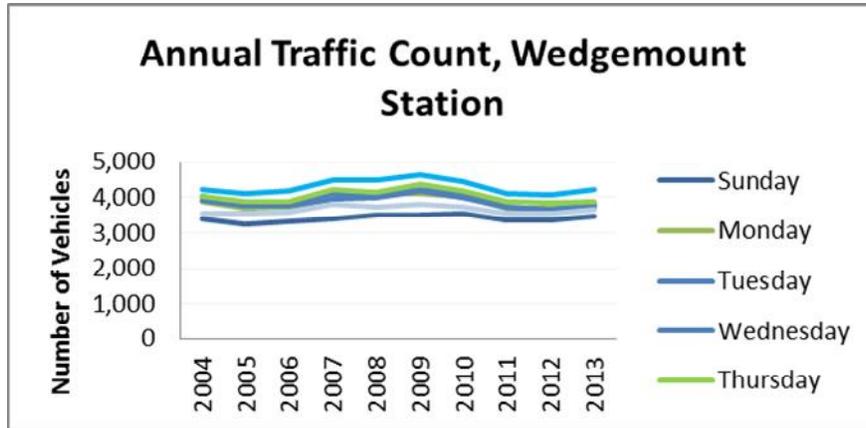


Figure 4-5 ‘Annual average daily traffic for each day at the Wedgemount traffic counting station’

Data Source: ‘BC Ministry of Transportation and Infrastructure 2015b’

Overall, traffic between Squamish and Whistler is about 3 times higher than traffic north of Whistler. These two sites also contain different monthly and weekly patterns. Between Squamish and Whistler, levels are highest in June and July with a second peak in early spring and weekly between Friday and Sunday. Wedgemount sees a peak in June and July and weekly on Fridays. The author suggests that traffic south of Squamish likely resembles the Squamish-Whistler patterns but there are no stations for verifying.

#### 4.4 Meteorological Characteristics

The following section summarizes the typical MET conditions within the airshed. MET conditions are important parameters to consider when analysing air pollution since they affect the level of air pollution. Precipitation shifts pollutants from the air into water, thereby reducing ambient concentrations (Yoo et al. 2014). Thus, periods of high precipitation can result in low pollution readings—even the amount of pollution emitted remains the same. Conversely, pollution accumulates during extended dry periods. Wind speed also affects air pollution levels. High wind speeds can disperse contaminants into or out of the airshed (Queensland Government 2013). Generally, periods of low wind speeds lead to increases of pollution, especially when combined with dry periods. Temperature can also increase or decrease pollution. Higher temperature can increase pollution levels—especially for secondary pollutants since their chemical reactions occur faster (Queensland Government 2013). Furthermore, temperature inversions will prevent wind from mixing and often lead to build ups of pollution. Wind direction is important since this, combined with wind speed gives information about the source of pollution.

The Sea-to-Sky Airshed contains four stations that collect MET readings<sup>11</sup>. Instruments continuously collect data for at least one of the following parameters: humidity, precipitation, temperature, scalar wind speed and vector wind direction<sup>12</sup>.

Across the stations monitoring temperature in the airshed (Langdale, Horseshoe Bay and Squamish), temperature is highest in July and August and lowest in January and December (figure 4-6). Over a typical day, the temperature is lowest at 6 am and steadily increases its peak between 2 and 4 pm (figure 4-7). Average monthly graphs for Horseshoe Bay are depicted below, figures for the remaining stations can be found in the appendix plate D, object D-4 to D-7 since the graphs are similar.

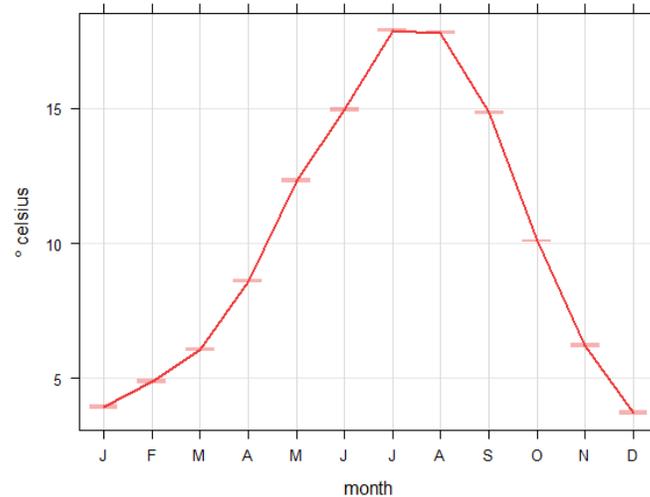


Figure 4-6 'Average monthly temperature, Horseshoe Bay 2002-2013'

Data Source: 'Ministry of Environment 2015c'

<sup>11</sup> The Port Mellon station is administered by industry, and given their different data collection and QA/QC methods it has been removed this summary of the the airshed's meteorological conditions since data quality is not reliable.

<sup>12</sup> Scalar wind speed and vector wind direction were selected from the multiple similar wind parameters because these parameters are typically used for visually plotting the data, and; the vector directional parameter properly plots the values around 360 degrees.

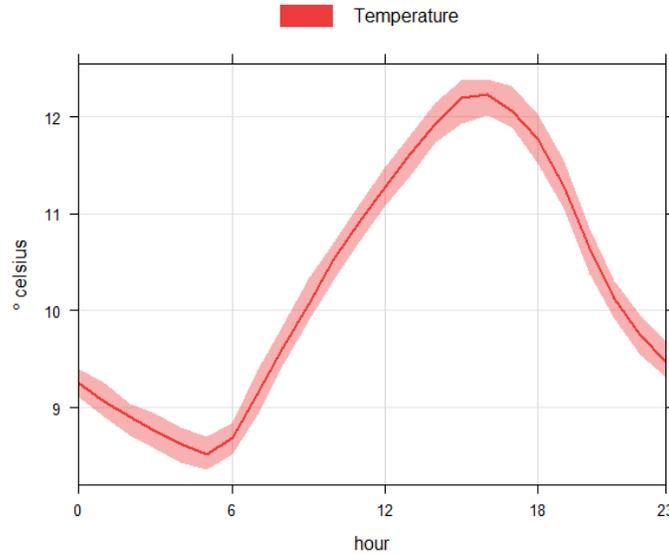


Figure 4-7 'Average daily temperature for 2002-2013 at Horseshoe Bay station'

Data Source: 'Ministry of Environment 2015c'

Langdale has the highest humidity in January and the lowest in July and May (figure 4-8). The Horseshoe Bay and Squamish stations offer the same seasonal trend, although Horseshoe Bay's peak is in December and Squamish's is in November<sup>13</sup>. The typical daily pattern in humidity across all stations is a peak around 6 am and a low around 3pm (Langdale, figure 4-9 is a representative illustration).

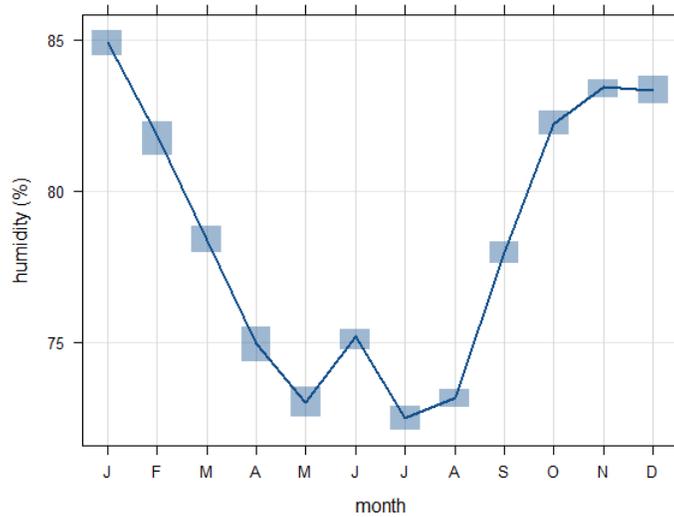


Figure 4-8 'Average monthly humidity trend at Langdale station'

<sup>13</sup> Since the graphs that support this observation are similar please refer to appendix plate D, object D-8 to D-11 should the reader desire reference.

Data Source: 'Ministry of Environment 2015c'

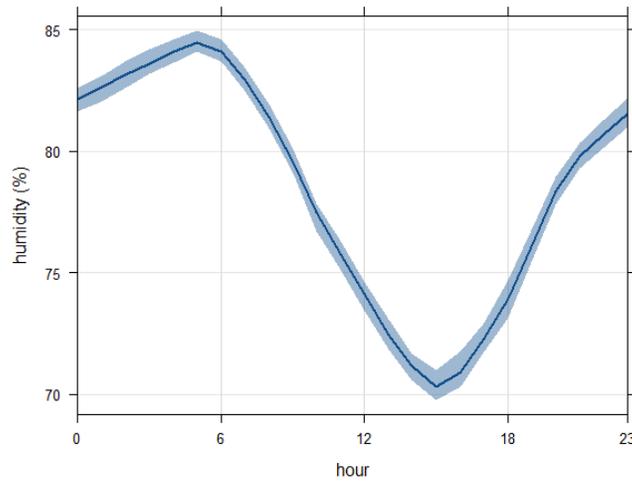


Figure 4-9 'Average daily humidity at Langdale station'

Data Source: 'Ministry of Environment 2015c'

For identifying airshed wind patterns we can observe wind roses for two three stations: Langdale and Horseshoe Bay (Squamish's wind direction data was inaccurate between 2001 and 2013). Wind roses show the distribution of wind speeds from various directions. Given the land, sea, mountains and valleys within the airshed, this creates a variety of different patterns throughout the airshed, and these vary by season. Unfortunately, given the low number of stations with reliable MET data, the author is not able to develop a cohesive picture of airshed wind patterns and can only discuss the two stations.

At the Horseshoe Bay station, winds patterns follow two main patterns. The highest velocity winds come from the south-western direction during summer and spring (figure 4-10). On the other hand, low velocity winds originate from the north to north-eastern direction. Winter predominantly consists of low winds from the north-east.

### Seasonal Wind Roses for Horseshoe Bay Station

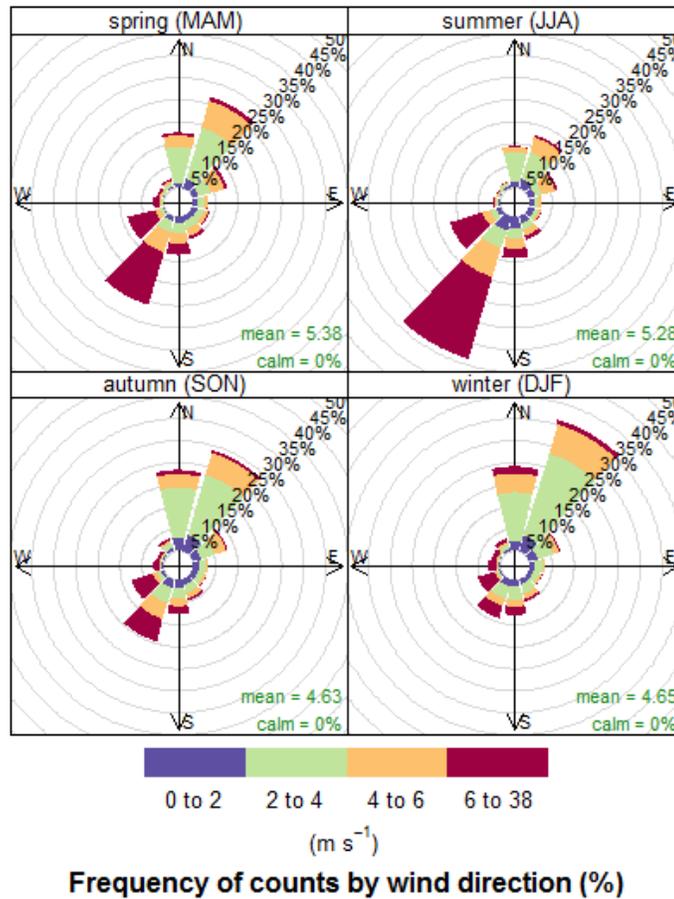


Figure 4-10 'Seasonal wind roses for Horseshoe Bay station, 2002-2013'

Data Source: 'Ministry of Environment 2015c'

Daily and nightly wind patterns at the Horseshoe Bay station vary dramatically. Daytime contains the majority of high velocity winds, and these come from the south-western direction (figure 4-11). The amount of high daytime winds is almost equally balanced by the amount of low velocity winds, and interestingly these originate from the opposite direction. At night, low velocity north, north-eastern winds dominate, with little wind coming from other directions.

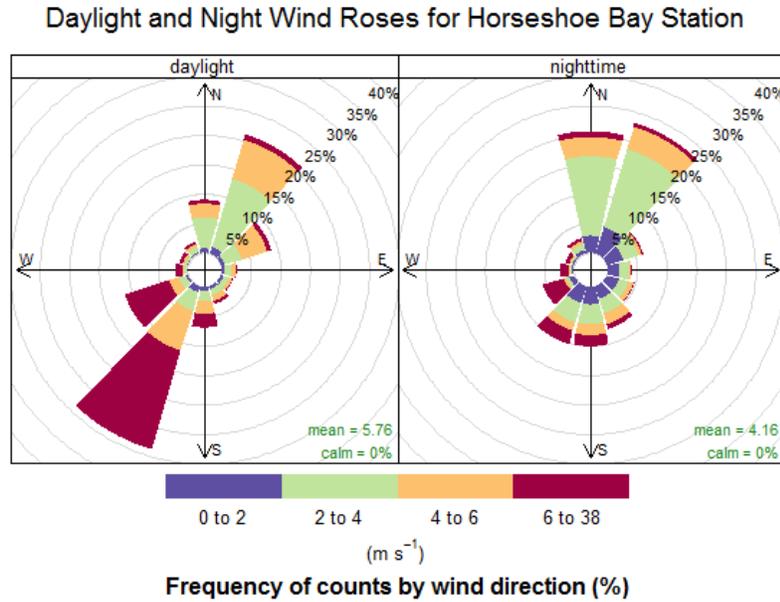


Figure 4-11 'Wind roses for daytime and nighttime wind patterns at Horseshoe Bay station, 2002-2013'

Data Source: 'Ministry of Environment 2015c'

At the Langdale station, most high velocity winds come from the south during summer, although spring has a significant amount as well (figure 4-12). These high velocity winds typically occur during daylight hours (figure 4-13). Low velocity winds consistently blow from the west to north-western direction throughout each day, across all seasons.

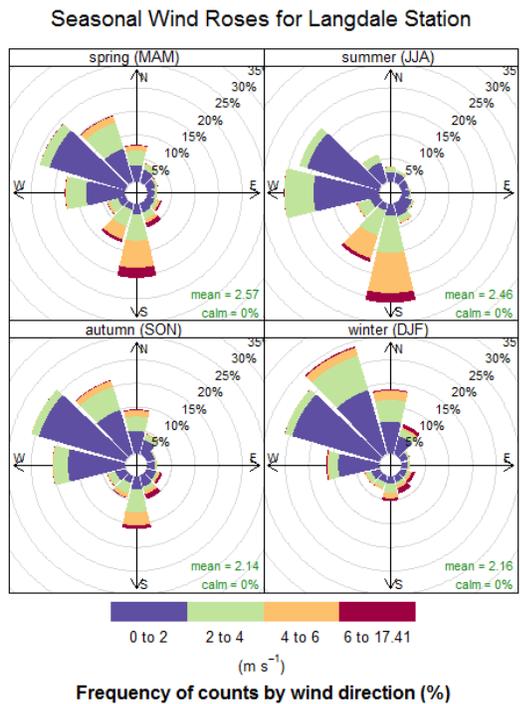


Figure 4-12 'Seasonal wind roses for Langdale station, 2002-2013'

Data Source: 'Ministry of Environment 2015c'

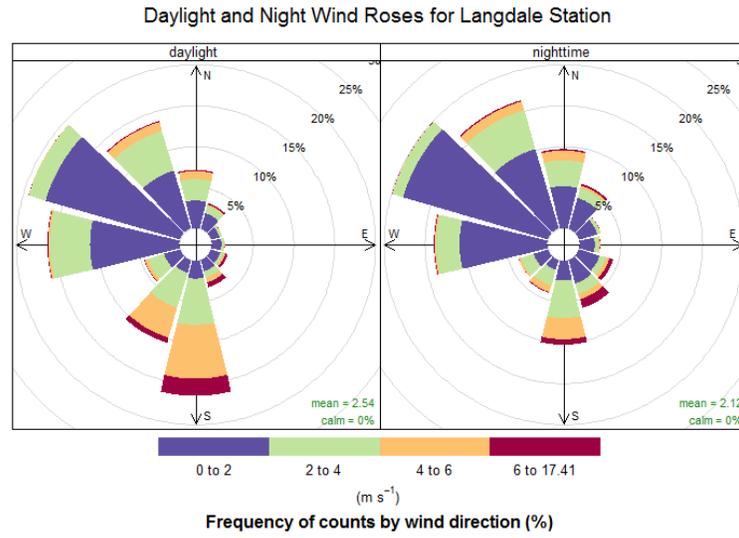


Figure 4-13 'Wind roses for daytime and nighttime wind patterns at Langdale station, 2002-2013'

Data Source: 'Ministry of Environment 2015c'

## 5 Ambient Air Quality Analysis

The following chapter analyses continuous pollutant data collected throughout the Sea-to-Sky Airshed between 2002 and 2013 using a series of analytical steps. Each step contributes insight into pollutant trends, characteristics and significance that forms the basis for the monitoring and management recommendations in later sections. The 8 measured contaminants in the airshed. CO, NO, NO<sub>2</sub>, O<sub>3</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, and TRS will each be analysed. Pollutants are listed in alphabetical order of pollutant name, and since most pollutants are monitored by multiple stations, they are further sorted alphabetically by station name.

To provide context for the analysis, the basic characteristics of each pollutant are first summarized below. After, the contaminant analysis is elaborated in subsections, one for each type of analysis: station summaries, analysis of Canadian and B.C. ambient air quality objectives, boxplots, autocorrelation (ACF), STL, percentile trends, daily to monthly time variations, study of average hourly contaminant concentrations and pollution roses.

**Carbon Monoxide, CO:** is formed when fossil fuels undergo incomplete combustion. In urban areas such as Metro Vancouver, transportation creates the majority of CO emissions (Doerkson et al. 2013). CO emissions therefore tend to be highest near roads and highways and levels can mirror transportation patterns. This pattern is observed in the Lower Fraser Valley Airshed (Doerkson et al. 2013). Given the relationship between CO and traffic, this contaminant is sometimes used as a marker for traffic exhaust exposure (Bates et al. 2003). According to the same report, long-term chronic exposure can lead to cardiovascular problems.

**Nitric Oxide, NO:** NO reacts in the atmosphere in a matter of hours to form various compounds such as O<sub>3</sub> and HNO<sub>3</sub> (becomes acid rain). NO is a product of high temperature combustion—usually associated with motor engines. NO receives little attention in analysis or management since it is a precursor. In the airshed, NO is only recorded because the analyzers must monitor both NO and NO<sub>x</sub> to infer NO<sub>2</sub> levels (G. Veale personal correspondence February 26<sup>th</sup> 2015). However, the author deems an analysis of NO relevant since information about NO levels can provide background for the other pollutants.

**Nitrogen Dioxide, NO<sub>2</sub>:** is a red-brown, pungent smelling gas formed during high temperature combustion, like from transportation and industry. Nitrogen oxides can react to form PM<sub>2.5</sub> and ozone (BC Lung Association 2013). At least in Metro Vancouver, the key sources of NO<sub>x</sub> emissions are passenger vehicles, trucks, marine vessels and non-road engines (Metro Vancouver 2011). NO<sub>2</sub> exposure has been linked to lung disease, compromised lung function, aggravation of asthma, and increased risk of lung infection (BC Lung Association 2013, Bates et al. 2003).

**Ground level ozone, O<sub>3</sub>:** Ozone is a strong gaseous oxidant formed primarily when nitrogen oxides (NO<sub>x</sub>, of which NO<sub>2</sub> is included) react with volatile organic compounds<sup>14</sup> (VOCs). NO<sub>x</sub> and hydrocarbon reactions also can result in O<sub>3</sub>. Both reactions occur in the presence of sunlight and are faster at higher temperatures. Thus, high levels tend to occur during the

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<sup>14</sup> VOC is from natural sources (such as some types of urban vegetation) and solvents used in industrial, commercial and consumer products (Metro Vancouver 2011).

spring and summer. O<sub>3</sub> causes eye, nose and throat irritation, breathing difficulties, reduced lung function, increased respiratory infections, aggravate asthma and lead to premature death (BC Lung Association 2013, Bates et al. 2003). O<sub>3</sub> can also degrade rubber, and reduce the growth and productivity of some crops and vegetation. Throughout BC, motor vehicles are the major source of O<sub>3</sub> since they are primarily responsible for NO<sub>x</sub> and hydrocarbon emissions (BC Lung Association 2014).

**Particulate Matter under 2.5 µg/m<sup>3</sup>, PM<sub>2.5</sub>:** PM<sub>2.5</sub>, or fine particulate matter is less than 2.5 microns in diameter, and is small enough to penetrate deep into lungs. This is particularly important since PM<sub>2.5</sub> can enter airways that are too small for cilia and is therefore difficult to remove once inhaled and can also enter the bloodstream (BC Lung Association 2013). Some health consequences include decreased lung function, respiratory and cardiovascular health, and increased mortality and hospitalization (Bates et al. 2003). Some respiratory and cardiovascular impacts can cause long term effects (BC Lung Association 2013). PM<sub>2.5</sub> can also degrade visibility with the whitish haze it creates by scattering light. According to the 2004 Sea-to-Sky Ambient Air Quality Report, PM<sub>2.5</sub> comes from wood combustion (woodstoves, backyard burning, and prescribed burning), transport emissions (passenger vehicles, trucks, marine and rail engines), industrial sources and dust. In late summer PM<sub>2.5</sub> can also be transported from forest fires elsewhere in the province. This can lead to exceedances within airsheds distant to the fires. This happened in 2010 and 2011 when Metro Vancouver exceeded its 24 hour standard (Doerkson et al. 2013). Secondary PM<sub>2.5</sub> can also form through reactions such as NO<sub>x</sub>, SO<sub>2</sub> and ammonia (BC Lung Association 2013). Hot and sunny conditions increase secondary PM<sub>2.5</sub> formation (Doerkson et al. 2013).

**Particulate Matter under 10 µg/m<sup>3</sup>, PM<sub>10</sub>:** Sometimes referred to as inhalable particles (BC Lung Association 2014), PM<sub>10</sub> consists of solid particles or liquid droplets with a diameter smaller than 10 microns. Although larger than PM<sub>2.5</sub>, particles are still small enough to be inhaled into our lungs. The difference is the PM<sub>10</sub> enters less area that is free of cilia (BC LUNG) and can therefore be more easily expelled once inhaled. Some examples health effects are exacerbated heart and lung diseases, aggravated asthma, increased risk of cancer, and higher daily mortality (Bates et al. 2003). It also has been linked to corrosion, vegetation impacts and reduced visual air quality (Doerkson et al. 2013). The 2002 Sea-to-Sky Ambient Airshed study cited wood burning, vehicle exhaust, industrial sources and dust as PM<sub>10</sub> sources within the airshed. More recently, Metro Vancouver's PM<sub>10</sub> was reported to typically consist of nitrates, sulphates, and diesel exhaust (Doerkson et al. 2013). This was mainly emitted from residential wood heating and industry followed by construction dust, demolition dust, and windborne particles from agriculture.

**Sulphur Dioxide, SO<sub>2</sub> :** is a colourless odorous<sup>15</sup> gas that can react in the air to create acidic by-products like sulphuric acid or secondary PM<sub>2.5</sub>. Sulphuric acid is known for creating acid rain. High levels of SO<sub>2</sub> can be an irritant and aggravate asthma and respiratory symptoms (BC Lung Association 2014; Bates et al. 2003). Additional effects are the subject of contested studies (Bates et al. 2003). BC-wide, SO<sub>2</sub> is typically emitted from metal smelting, the pulp and paper industry, the upstream oil and gas sector, refineries, and marine sources (BC Lung Association 2013). In the past, the main source of SO<sub>2</sub> was point sources from the pulp and paper industry (contributing to about 70% of emissions) (Meyn 2004). Marine vessels were another notable source due to the combustion of sulphur containing fuels.

**Total Reduced Sulphur, TRS:** TRS consists of a group of sulphurous compounds, mainly: dimethyldisulphide, dimethyl sulphide, methyl mercaptan, and hydrogen sulphide. TRS is not

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<sup>15</sup> At concentrations greater than 1000µg/m<sup>3</sup>

typically associated with health impacts, although the 2004 Sea-to-Sky Ambient Air Quality Monitoring Report cites that living in close proximity to TRS sources leads to more coughs, headaches and respiratory infections than communities without such sources. The more common issue with TRS is our ability to detect its rotten egg-like odour at very low concentrations (as little as 5 to 6 ppb). The B.C. objectives used in this study are around this level to help prevent these nuisance odours. Usual sources of TRS include the pulp and paper industry, petroleum refineries, and natural sources like swamps (Meyn 2004).

## 5.1 Station Summaries

Like the first step in the MET analysis, the first analytical consideration is to conduct an overview of each station. Like performed for the MET parameters, each station analyser was reviewed for data completeness. Too little recorded data disqualified some analyzers from certain analytical steps. Reviewing data completeness is also important since air quality objectives require at least 75% data completeness. Data gaps also signify instrument malfunctioning, power outages or errors, and are markers for improving monitoring efforts.

The station summaries made for pollutant parameters are the same format as used for studying MET parameters. Figure 5-1 stands as an example. Analysing this chart enables us to observe that the Horseshoe Bay station contains only two pollutant analyzers, and these began to collect data one quarter through 2002. The percent of data captured is high, and all years can be used for calculating exceedances in air quality objectives. The largest gap occurs at the end of 2007, but this is not during the seasonal peak pollution period and therefore should not unduly impact subsequent operations. The fluctuation in the time series CO data (the top right chart) demonstrates strongly seasonal data while PM<sub>2.5</sub> is indeterminate. The majority of CO measurements register around 180 ppb, while the distribution of PM<sub>2.5</sub> is under 10 ppb and peaks between 3 to 4 ppb. Both distributions are skewed to the right (or positively skewed) so further analysis must treat the collected data as such.

### Summary Plot for Horseshoe Bay Station Pollutant Data

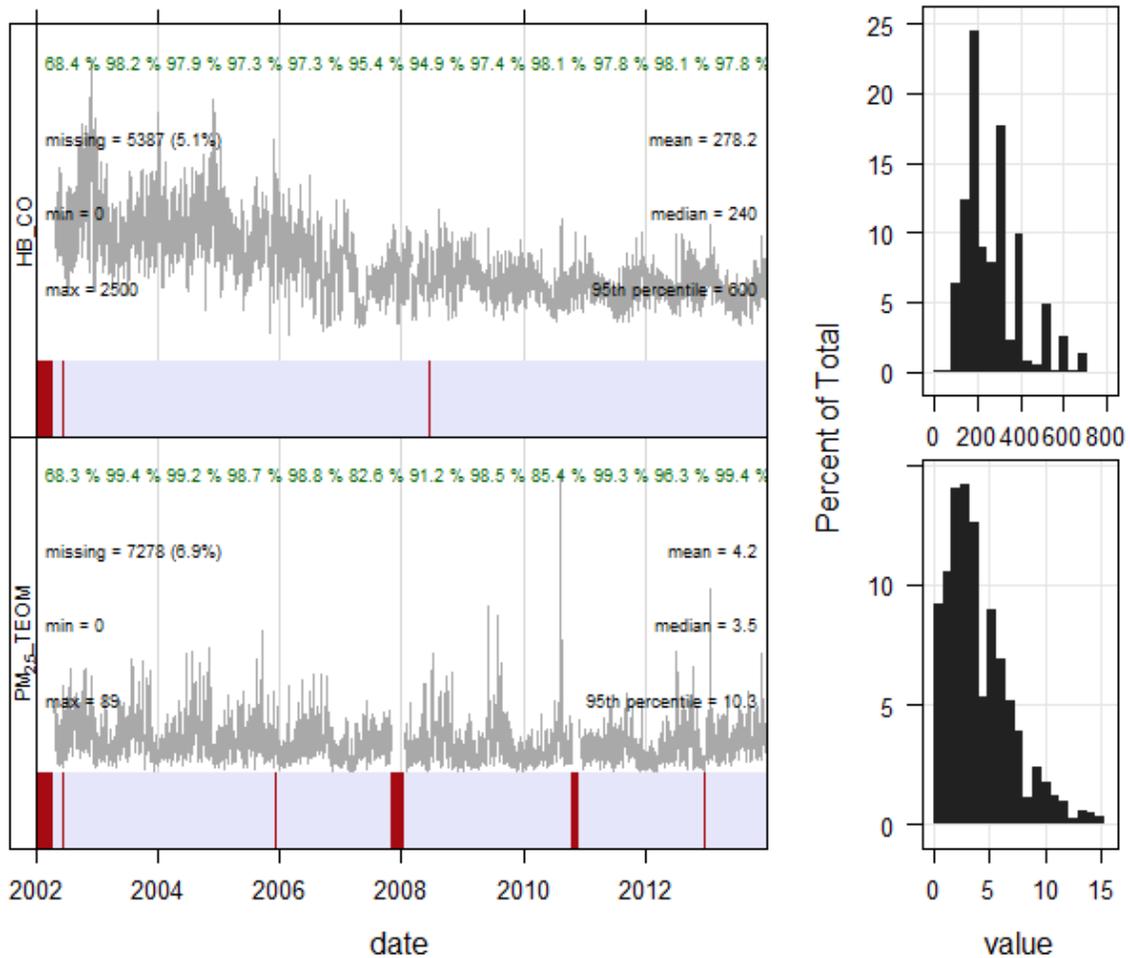


Figure 5-1 'Summary plot of pollutant measurements at Horseshoe Bay station'

Data Source: 'Ministry of Environment 2015c'

Analysis of the remaining station summary plots is below, while corresponding charts are in the appendix, plate E, object E1 to E3.

Langdale measures far more pollutants than Horseshoe Bay: NO, NO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub> (BAM), SO<sub>2</sub> and TRS. The data capture rate is consistently high, and all years of recorded data can be used for evaluating air quality objectives. That being said, there is a fair number of smaller gaps in the data and some of these gaps fall during peak pollution periods (such as for PM<sub>10</sub> and TRS). This would be of concern if annual summaries were performed with the data. Since our study uses 12 years of data, a portion missing of one year is not cause for concern for all but the study of average hourly concentrations. There are also only two years of PM<sub>2.5</sub> (BAM) measurements so this data should not be used for analyzing long term trends in this study. Like Horseshoe Bay's histograms, all Langdale's pollutant distributions are skewed to the right.

The Squamish station also monitors a large number of pollutants: NO, NO<sub>2</sub>, O<sub>3</sub>, PM<sub>10</sub>, PM<sub>2.5</sub> (BAM), PM<sub>2.5</sub> (TEOM), SO<sub>2</sub>, TRS. Data capture is lower, and at times this prevents the calculations for air objective exceedances from being valid. This includes: the first year of analyzer operation for NO and NO<sub>2</sub> (2005), both 2002 and 2003 for ozone, and 2006 PM<sub>10</sub> measurements. 2009 SO<sub>2</sub> and 2013 PM<sub>2.5</sub> (TEOM) measurements barely qualify for the assessment because they capture 76.1% and 76.2% of data respectively. Many other years are also fairly low. All data appear to have seasonal variations, although the pattern for TRS is less defined. All data distributions are skewed to the right with the exception of TRS—and this only occurs since the TRS readings are too low to be properly expressed using the histogram defaults.

The Whistler Station measures NO, NO<sub>2</sub>, O<sub>3</sub>, PM<sub>2.5</sub> (BAM) and PM<sub>2.5</sub> (TEOM). The initial year of data collection for each pollutant must be eliminated from calculating exceedances in air quality objectives since in each case the analyzers began recording too late in the year. Year 2007 for NO and NO<sub>2</sub> must also be eliminated due to low data capture. All pollutants appear to have seasonal patterns except for PM<sub>2.5</sub> (TEOM) which at least from this plot appears indeterminate. Once again data are skewed to the right.

## 5.2 Analysis using Canadian and British Columbian Ambient Air Quality Objectives

Ambient air quality objectives are a tool used by many management authorities to assess air quality. Throughout Canada there are a collective of federal, provincial, municipal and airshed objectives. These objectives are based off of a number of considerations—human health being of utmost importance, with added consideration given to impacts on infrastructure, public nuisance, visual air quality and ecosystems (Environment Canada 2015). In BC, objectives are used as a common gauge for current and historical air quality, as tools to inform decisions about environmental impact assessments and authorizations, to enhance airshed planning and management, to guide regulation, and to develop strategies for managing air pollution episodes (MoE 2014). These limits are non-statutory (not legally binding). Further, these objectives should not be viewed as a license to pollute up to the given level. Instead, airshed management strives to reduce all levels as much as possible, especially since research is still ongoing about the consequences of various contaminants.

The standards that are used throughout BC are a mixture of Canadian Ambient Air Quality Standards (CAAQS), National Ambient Air Quality Objectives (NAAQO), and Provincial Air Quality Objectives (Provincial AQOs). In 2014 new provisional objectives were released. Municipalities can create their own as long as they are stricter than existing standards, as is the case with Metro Vancouver (Doerkson et al. 2013). The Sea-to-Sky Airshed follows a mixture of federal and provincial objectives, shown in table 5-1 below (black objectives are actively used for the analysis, grey are for reference):

Table 5-1 Canadian and British Columbian ambient air quality objectives

| Contaminant | Avg. Period | Criteria  | Level | Air Quality Objective |        | Date Adopted |
|-------------|-------------|---|-------|-----------------------|--------|--------------|
|             |             |   |       | µg/m <sup>3</sup>     | ppb    |              |
| CO          | 1 hour      | Pollution Control Objective for food processing, agriculturally orientated and other misc. industries | A     | 14,300                | 13,000 | 1975         |
|             |             |   | B     | 28,000                | 25,000 |              |
|             |             |   | C     | 35,000                | 30,000 |              |

|                   |         |                                       |             |                           |                           |      |
|-------------------|---------|---------------------------------------|-------------|---------------------------|---------------------------|------|
|                   | 8 hour  |                                       | A<br>B<br>C | 5,500<br>11,000<br>14,300 | 5,000<br>10,000<br>13,000 | 1975 |
| NO <sub>2</sub>   | 1 hour  | Interim Provincial AQO                | -           | 188                       | 100                       | 2014 |
|                   | 8 hour  | Interim Provincial AQO                | -           | 60                        | 32                        |      |
| O <sub>3</sub>    | 1 hour  | NAAQO Maximum Acceptable Level        | Advisory    | 160                       | 82                        | 1989 |
|                   | 8 hour  | CAAQS                                 | -           | 123                       | 63                        | 2013 |
| PM <sub>2.5</sub> | 24 hour | Provincial AQO                        | -           | 25                        | -                         | 2008 |
|                   |         | CAAQS                                 | -           | 28                        | -                         | 2013 |
|                   | Annual  | Provincial AQO                        | AQO<br>Goal | 8<br>6                    | -                         | 2005 |
|                   |         | CAAQS                                 | -           | 10                        | -                         | 2013 |
| PM <sub>10</sub>  | 24 hour | Provincial AQO                        | -           | 50                        | -                         | 2005 |
| SO <sub>2</sub>   | 1 hour  | Interim Provincial AQO                | -           | 200                       | 75                        | 2014 |
| TRS               | 1 hour  | PCOs for the Forest Products Industry | A           | 7                         | 5                         | 1977 |
|                   |         |                                       | B           | 28                        | 20                        |      |
|                   | 24 hour |                                       | A           | 3                         | 2                         |      |
|                   |         |                                       | B           | 6                         | 4                         |      |

*Adapted from: 'MoE 2014'*

There is also a provincial AQO for formaldehyde but there are no measurements in the airshed to support evaluating this objective. There is no objective for NO. Despite the lack of objective, NO is still measured throughout the airshed because it represents an important precursor to other contaminants.

In many cases pollutants are subject to multiple objectives, and in these cases the strictest objectives were chosen. Further, since the objectives were established over a broad range of dates (many of which are partway through the study period) for the sake of simplicity only the most recent objectives are applied.

The majority of exceedances come from the Langdale TRS station: the 1 hour objective was exceeded 202 times and the 24 hour objective was exceeded 36 times between 2002 and 2013. The amount appears to jump upwards after 2007—possibly relating to equipment changes at the Howe Sound Pulp and Paper plant. There are also TRS exceedances in Squamish: 17 times for the 1 hr objective and 1 time for the 24 hr objective. Most exceedances occurred before 2006, and since the nearby Forest Western Products pulp mill closed in 2006 this was likely the primary cause. After 2006 there were 4 exceedances of the 1 hr objective, and these could be from diesel idling near the station.

Apart from TRS, the airshed has few exceedances. Ozone at the Squamish station exceeded the 1 hr objective 3 times in the spring of 2009 and Squamish PM<sub>10</sub> exceeded its 24 hr objective twice in 2010 (on August 5<sup>th</sup> and November 22<sup>nd</sup>). It is possible that ozone exceeded the standard in 2009 due to heavy highway construction in preparation for the 2010 Olympics. The August PM<sub>10</sub> exceedance could be from the high forest fires in the end of July and throughout August. The November exceedance is less clear—perhaps local wood stove combustion.

Besides reporting exceedances, it is also important to note near exceedances since this can signal future issues—especially should population and traffic continue to grow. In this regard, PM<sub>2.5</sub> at all stations approached the objectives and should be a focus of monitoring and management. Whistler PM<sub>2.5</sub> very nearly surpassed the 8 ppb annual objective in 2010

(recording 7.7 ppb). PM<sub>2.5</sub> dropped every subsequent year, though additional years are necessary in order to conclude whether a trend exists. At Squamish, annual average PM<sub>2.5</sub> levels fluctuated between 5.6 and 7 ppb during the 4 years of measurement. Langdale only had two full years of measurements and thus does not yet qualify for calculating the objective. From preliminary years of data, Langdale's levels are similar to Squamish's. This approaches the standard and exceeds the provincial goal of 6 ppb. Should the standard be lowered in the future this will likely become a source of regular exceedances. In the years at followed, average Horseshoe Bay's average annual level over the study was 4.1, with the highest annual average being 4.9. While the values are not as high as the other stations, they should be monitored along with any growth in key PM<sub>2.5</sub> sources.

In addition to the Squamish ozone exceedances, Squamish very nearly exceeded the 8 hour ozone objective in 2004. Most other years were also comparatively high. For the above reasons, and given the numerous detrimental impacts of O<sub>3</sub>, reducing existing levels should be a priority. Whistler O<sub>3</sub> also merits priority because the contaminant at this station consistently came within 13 ppb of the 8 hour limit. The Squamish station also has high 8 hour values (in addition to its 3 24 hour exceedances). In fact, in 2003 the standard was only missed by 1.4 ppb.

### 5.3 Boxplots

Like the MET analysis, boxplots were used to examine ranges, and whether significant differences exist between the ranges at different stations. One boxplot was created for each pollutant analyzer's data. Boxplots for the same pollutant were combined in one chart to facilitate comparisons between ranges. These boxplots are constructed using the same features as those made for the MET analysis: box centerline representing the median, upper box limit being the 75<sup>th</sup> percentile, and the lower bound being the 25<sup>th</sup> percentile. The whiskers extend to the range multiplied by the interquartile range. Outliers are excluded from all plots.

Figure 5.2 represents an example of the chart created for this type of analysis. After a survey of all the plots (appendix plate E, object E-4 to E-10), we must discount comparisons with the Whistler Function Junction boxplots since this temporary station has only a fraction of the sample size compared to the other stations. A different sample size can create boxplots with different characteristics than the other stations. Additionally, given the placement of the median, and the size of the upper bound and upper whisker, all plots confirm the positive skewing of data. Observations for each pollutant boxplot are described below:

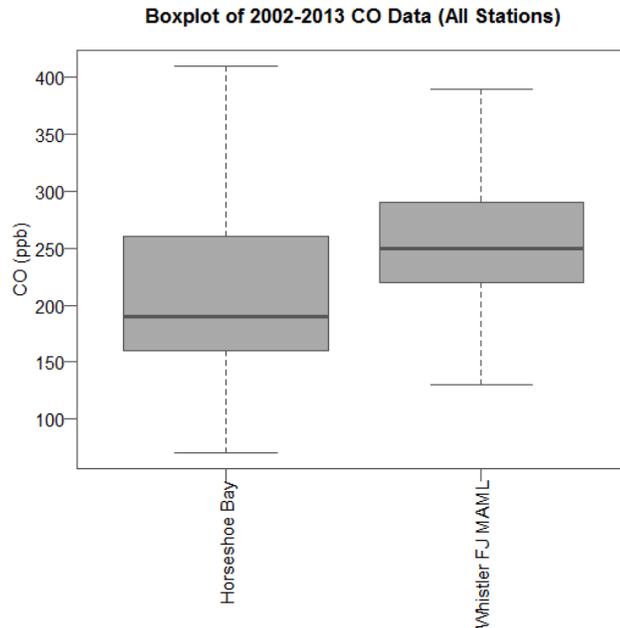


Figure 5-2 'Boxplots for CO measured in the Sea-to-Sky airshed'

Data Source: 'Ministry of Environment 2015c'

CO: The median pollution level of CO at the Horseshoe Bay station is around 190 ppb, and 50% of measurements fall between 155 and 260 ppb. This is very low compared to the objective. Even the upper whisker only hits 410 ppb (excluding outliers) which is far outstripped by the one hour Pollution Control Objective of 13,000 ppb. The mobile Whistler Function Junction station cannot be compared to Horseshoe Bay, but, we can observe that this small body of monitoring data also falls well below the objective.

NO: Langdale has less variation in NO concentrations than at the Squamish and Whistler Stations, though the median pollution varies little. Langdale's pollution generally varies between 0 and 5 ppb and the other stations between 0 and 11 ppb.

NO<sub>2</sub>: Overall, NO<sub>2</sub> pollution is low throughout the airshed. Squamish has the highest median concentration of NO<sub>2</sub> (being around 6 ppb), while the others have about 3 ppb lower. Langdale has a marginally smaller range. Generally most pollution falls between 0 and 17 ppb which is well below the Interim Provincial AQO of 100 ppb.

O<sub>3</sub>: Whistler has slightly higher median and upper whisker values compared to Squamish—communicating that ozone concentrations are slightly higher at Whistler than in Squamish. There is also more range in the Whistler pollution. Variation ranges between 0 and 63 ppb at Whistler and 0 and 51 ppb at Squamish. The median is 19 and 14 respectively. These one hour values fall well below the one hour NAAQO Maximum Acceptable Level, that if surpassed results in an air quality advisory. However, the upper range of Whistler O<sub>3</sub> measurements is the same as the 8 hour CAAQS objective. This means that even though the objective was not formally exceeded by having enough measurements over 63 ppb for 8 consecutive hours, a significant amount of data does approach this objective.

PM<sub>2.5</sub>: The variation between PM<sub>2.5</sub> analyzers is complicated by the use of different instrumentation. BAM, TEOM and DICOT can all record slightly different readings for the

same pollution levels. BAM instrumentation will record higher PM<sub>2.5</sub> values than TEOM because its different method of measurement captures more PM<sub>2.5</sub> components (G. Veale, personal correspondence March 19<sup>th</sup> 2015). We can see this difference reflected by the two trends in PM<sub>2.5</sub> boxplots: TEOM has lower average values while BAM records higher values. BAM boxplots also showed more variation in recorded measurements. All in all, the BAM and TEOM medians differ around 3 µg/m<sup>3</sup> while the BAM's variation tends to have an additional 5 µg/m<sup>3</sup>. The majority of PM<sub>2.5</sub> measurements range between 0 and 15 µg/m<sup>3</sup>.

PM<sub>10</sub>: Of the two PM<sub>10</sub> analyzers in the airshed, the one at Langdale records smaller variation in pollutant levels compared to Squamish. This translates into much of Langdale's levels ending around 22 µg/m<sup>3</sup> while Squamish's extends almost double. That being said, the median changes little between the two stations (about 5 µg/m<sup>3</sup> lower). This leads to the upper limit of Squamish's PM<sub>10</sub> data approaching the 24 hour Provincial AQO of 50 µg/m<sup>3</sup>. Should the length of consecutively high measurements increase, this could be an issue.

SO<sub>2</sub> and TRS: SO<sub>2</sub> and TRS show less than 1 ppb in station differences and are therefore insignificant since this is beyond the instrument's precision (G. Veale, personal correspondence May 14<sup>th</sup> 2015). The upper whisker of SO<sub>2</sub> data extends up to 2.5 ppb, which is but a fraction of the 75 ppb hourly Interim Provincial AQO. The upper whisker of the SO<sub>2</sub> boxplot of the mobile Whistler Function Junction station falls below 0.5 ppb, indicating imperceptible levels over the Vancouver Olympics. The maximum whisker for TRS is 1.5, showing well under the hourly 5 ppb objective, and slightly under the 24 hour objective.

## 5.4 Examining Contaminant Autocorrelations

Air pollution measurements are not independent of each other. This means that at least some portion of pollution from a given hour will carry over into subsequent hours. This characteristic is known as persistence (Meko 2015). When discussing trends and possible causes of pollution, knowing how long values carry over is an important consideration. It also helps to predict how long a given pollutant may remain in the airshed—giving us more information about the duration of high pollution episodes. Autocorrelation charts also help define repetitive cycles—specifically the length of time between such cycles and how correlated the data are to one another.

Two autocorrelation charts were made for each analyzer's data to show weekly and seasonal autocorrelation trends. Figure 5-3 shows the weekly autocorrelation chart made for Horseshoe Bay station CO readings and figure 5-4 charts the annual autocorrelation. The left-most value for all charts will always have a correlation of one since the data are compared to an identical set of data. The next correlation value shows the data compared to the same data, but with a one hour time lag.

On the Horseshoe Bay chart we can see that this second value is very high (almost 0.8) which means that readings are usually quite similar to the readings of the previous hour. The same can be said for the two hours after that. We can thus say that pollution readings that are separated by several hours or less are strongly positively correlated, in other words, persistent. We can also observe a peak in similarity when values are separated by 24 hours and a secondary lower peak half way between each 24 hour lag. This communicates that CO concentrations have a fairly strong daily pattern, with a lesser mid-day similarity in readings. On the plot correlating data with up to a year lag, we can observe four peaks in positive correlation for each month. This translates into a weekly similarity in readings—potentially reflecting weekly traffic patterns.

The mobile Whistler Function Junction station demonstrates the same 24 hour similarity in readings and also that data separated by several hours or less are persistent.

The patterns for the other pollutants are described below, and their ACF charts can be found in the appendix plate E, object E-11 to E-52:

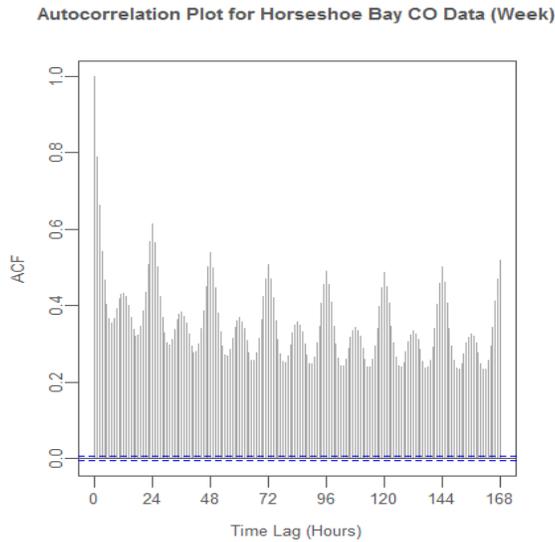


Figure 5-3 'Autocorrelation plot for Horseshoe Bay CO data, showing a lag of up to one week'

Data Source: 'Ministry of Environment 2015c'

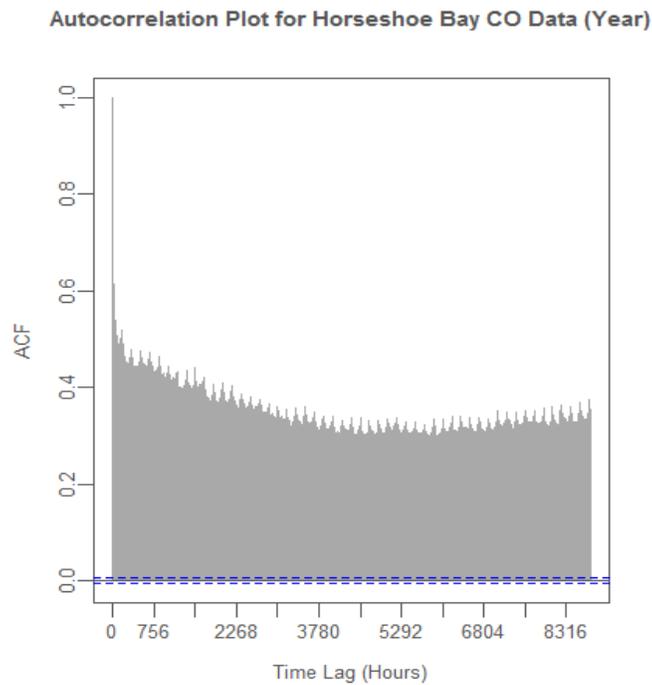


Figure 5-4 'Autocorrelation plot for Horseshoe Bay CO, with a lag of up to one year'

Data Source: 'Ministry of Environment 2015c'

NO: Readings that are separated by 24 hours have peaks of significantly positive correlation at all stations across the airshed. This means that the level of NO at, for example, 6 am is typically similar to other readings at 6 am. At the Squamish and Whistler stations, the persistence of a given value of pollution appears to affect readings up to 24 hours later. On the other hand, Langdale's persistence is only 5 hours or less. Squamish is the only station to demonstrate a weekly repetition in pollution values—this could perhaps suggest a higher contribution of traffic emissions or more variation in Whistler's weekly patterns. Seasonally, both Squamish and Whistler show that data is similar to data a year later, and significantly dissimilar to data half a year separated. This could translate to, for instance, data being high in the summer and low in the winter—thus exhibiting seasonality. All in all, the ACF graphs illustrate that there can be up to three different NO patterns (daily, weekly and seasonal), and that the pollution profiles at each station differ.

NO<sub>2</sub>: Once again, all stations demonstrate a 24 hr pollution pattern. The Whistler Function Junction mobile station has an additional secondary smaller peak in positive correlation at each half day mark, although given the small amount of measurements this could be an anomaly. Persistence is up to a day and a half, with Langdale having the shortest. Squamish appears to have a weekly pollution pattern and mild seasonality whereas Whistler lacks a seasonal pattern but has pronounced seasonality. Langdale's chart is inconclusive.

O<sub>3</sub>: O<sub>3</sub> has the most exaggerated daily and seasonal patterning out of all the pollutants. This means that the O<sub>3</sub> patterns should be the easiest to detect out of all the trends because the difference between the peaks and troughs of the cycle should be the most extreme. Persistence lasts with decreasing intensity until about half a day. Weekly trends are imperceptible—at least from these charts.

PM<sub>2.5</sub>: While all stations show clear daily pollutant cycles, Whistler shows the greatest variation in its correlation values. Horseshoe Bay and Squamish BAM show the least while the Langdale and Squamish TEOM patterning falls in between. Persistence lasts longer than other contaminants with periods as long as 2 to 2.5 days. All ACF charts indicate at least some degree of seasonality except for the Whistler TEOM data (although the BAM shows some seasonality). Once again we can observe a discrepancy in the data characteristics between the BAM and TEOM instruments.

PM<sub>10</sub>: Both Langdale and Squamish PM<sub>10</sub> pollution levels have a daily pattern, have persistence of up to two days and have well defined seasonality.

SO<sub>2</sub>: SO<sub>2</sub> levels at Langdale and Squamish follow a well-defined daily pollutant cycle and show persistence of just over 24 hrs—with Squamish's lasting several hours longer. On the other hand, the temporary station at Whistler Function Junction shows peaks in positive correlation every half a day but this is likely result of levels being below the instrument's precision. Additionally, correlation decreases as the week progresses instead of settling into a consistent daily pattern after a day or two. Langdale does not show an annual cycle whereas the Squamish station shows a very slight seasonality.

TRS: The TRS monitors at Langdale and Squamish communicate that pollution has a slight daily cycle and persistence of around one day. There is no seasonality.

## **5.5 Application of Seasonal-Trend Decomposition Procedure Based on Loess**

After having studied the persistence and cycles in pollution levels, we need to gather information about the relative influence seasonal cycles, long term changes, and stochastic events. This can be accomplished using seasonal-trend decomposition procedure based on Loess (STL). Figure 5-5 shows one of the charts created to study the STL, and additional STL charts for the data from each pollutant analyzer can be found in the appendix, plate E, object E-53 to E-71. It should be noted that the monitoring period of the mobile Whistler Junction monitoring station was not long enough to make STL plots.

Every STL chart created for this study first plots the pollution over time, then extracts and plots the seasonal variation below the first plot. A third plot extracts long term variation and steps in measurement levels. The final plot shows the remaining data after the seasonal and long term components have been removed. The remainder thus points to other influences on the data such as stochastic events (Cleveland et al. 1990). The grey bars on the right of each chart denote the scale. The larger the scale the more magnified the plots are and the less that aspect affects the pollution measurements. As such, we can make observations about what most and least affects pollution levels throughout the airshed and can focus management and policy efforts accordingly.

### STL Chart for Horseshoe Bay CO

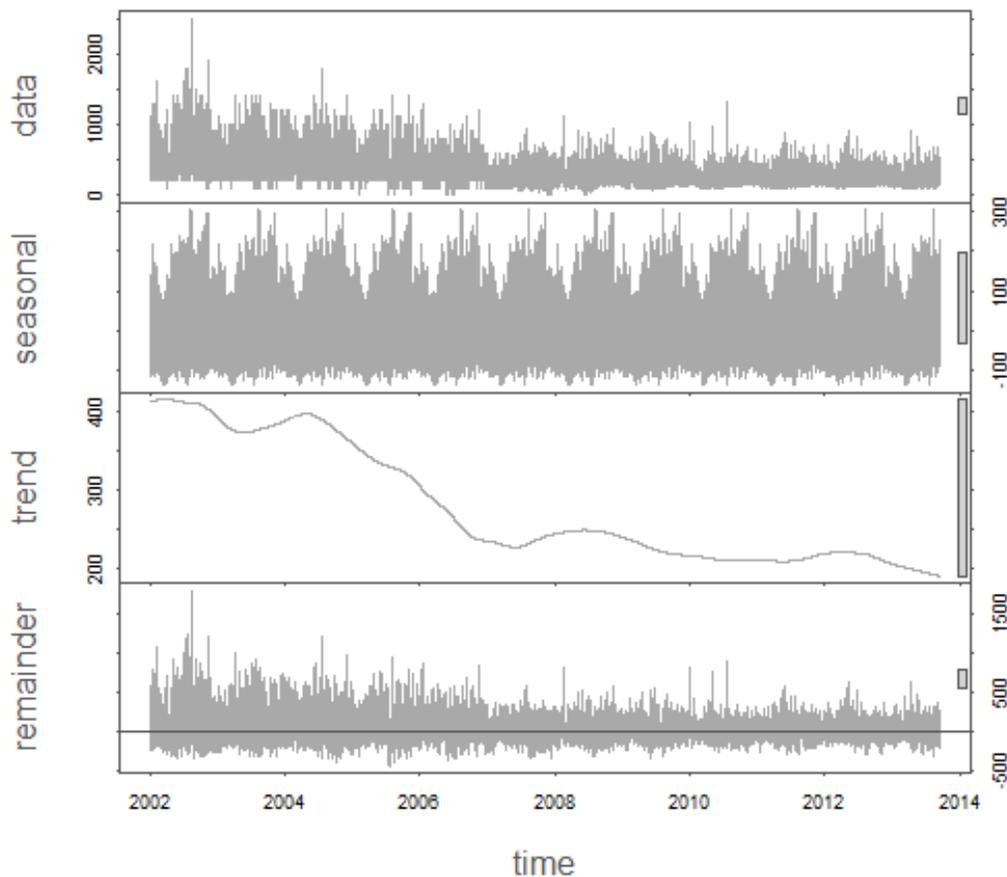


Figure 5-5 'Chart of time series decomposition by Loess for Horseshoe Bay CO'

Data Source: 'Ministry of Environment 2015c'

According to figure 5-5, the remainder constitutes the largest variation of CO levels at Horseshoe Bay, while seasonal changes are of medium import. Long term changes only attribute to a very small amount of variation, but that being said, there does appear to be a downwards trend by about 200 ppb over the study period. The majority of the decline was between 2004 and 2007.

The observations about the other pollutants are detailed in the pollutant categories below:

NO: Pollutant levels for all monitors in the airshed are strongly affected by variation in the remainder. The affect of seasonality also plays a key role in pollutant levels. In terms of long term changes, there is an 8 ppb decline in Whistler NO, but compared to the magnitude of the other variations this change is negligible. Other stations demonstrate no long term trends.

NO<sub>2</sub>: Like NO, the the remainder most strong influences the variation in pollutant levels. Seasonality continues to play a significant role, but in the case of NO<sub>2</sub>, its role is about two times smaller. Once again, Whistler shows a negligible downwards longterm trend (declining only 5 ppb). All others have no long term change.

O<sub>3</sub>: The remainder also most strongly influences O<sub>3</sub> data, while seasonality exerts between 2 to 3 times less of an impact. Together these two components drive the variation of O<sub>3</sub> levels in the airshed.

PM<sub>2.5</sub>: Throughout the airshed, the remainder plays the largest role in PM<sub>2.5</sub> levels. Seasonality plays a strong secondary role, being by far the strongest at Langdale. Long term trends are absent at all stations.

PM<sub>10</sub>: The remainder constitutes the largest variation of PM<sub>10</sub> throughout the airshed, followed by seasonal changes. There are no long term trends.

SO<sub>2</sub>: SO<sub>2</sub> variation also mainly comes from the remainder component. Variation from seasonality is small (the largest seasonal change being 3 ppb or less). There are no long term changes.

TRS: The remainder most affects the pollution changes of TRS throughout the airshed. There is insignificant seasonality and no long term trends.

## 5.6 Percentile Plots

Although there were no long term variations in any of the pollutants throughout the airshed (with the exception of a relatively small change in CO) this does not conclusively point to the absence of long term trends. However, because the data for each pollutant were analyzed together, changes in the various levels of concentration could be masked. This was in fact found to be the case in Doerkson et al. 2014. In order to determine whether similar changes occur, this next step of analysis plots each station's mean monthly pollutant values along three percentiles: 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup>. Plotting these values over time shows changes in the low, mid and upper ranges of the data. These lines are smoothed to show monthly and long term variation. The plots also include a 95% confidence interval, denoted by the shading around the long term trendline. A sample of one percentile plot is below (figure 5-6), and charts for all other pollutants are in the appendix, plate E, object E-72 to E-89.

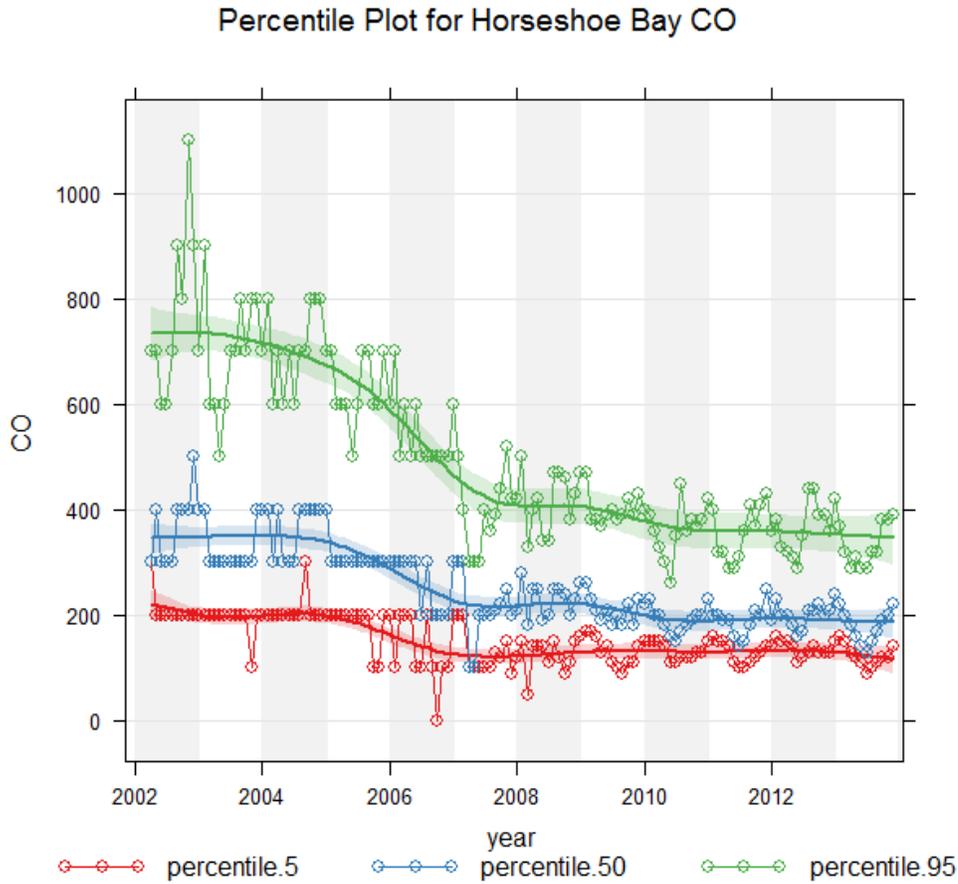


Figure 5-6 '5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile values of Horseshoe Bay CO data, smoothed by year and month'

Data Source: 'Ministry of Environment 2015c'

By observing figure 5-6, we can see the downwards trend between 2004 and 2007 that was shown in the previous section's STL chart also displays by all the percentile trendlines. The percentile plot shows that most of this change occurs in the higher CO levels because the 95<sup>th</sup> percentile trend decreases the most. In fact, the decline in 95<sup>th</sup> percentile values began occurring earlier than reflected by the STL chart but this decrease is masked by the delayed change in the lower values. From this chart, we can attribute the longterm change in CO levels to reductions starting in 2001 in source(s) that contribute to less frequent episodes of high concentration.

Analysis of the remaining contaminant percentiles are elaborated in the subsections below:

NO: Whistler's 95<sup>th</sup> percentile of NO decreased more than Squamish's (about 20 ppb compared to 7 ppb) while the lower percentile trendlines remained constant. At Langdale all trendlines remained the same<sup>16</sup>.

<sup>16</sup> Langdale's 95<sup>th</sup> percentile trendline did decrease visually but the 95% confidence intervals still overlapped deeming the change negligible.

NO<sub>2</sub>: For this pollutant, observations for each station differ. Whistler experienced a very slight decline in its upper and mid percentile trends. Squamish showed a peak in NO<sub>2</sub> concentration across all percentiles at the beginning of 2008, but levels decreased afterwards to result in no net change. The 2008 peak was most pronounced in the 95<sup>th</sup> percentile. For Langdale, no significant change occurred in any trendline.

O<sub>3</sub>: After accounting for confidence intervals, there are no significant changes across any percentiles for ozone in the airshed.

PM<sub>2.5</sub>: Horseshoe Bay shows no significant changes in any percentiles. There are no changes in any of Whistlers percentiles for both the TEOM and BAM instruments. The Squamish PM<sub>2.5</sub> BAM shows no change but additional years of data are needed to be more conclusive. Both the Squamish TEOM and the Langdale BAM have too few years of data to make a statement—indeed the small amount of data has resulted in charts with more of a seasonal appearance of longterm trendline smoothing.

PM<sub>10</sub>: Squamish's 95<sup>th</sup> PM<sub>10</sub> percentile shows a slight increase in values (less than 10 µg/m<sup>3</sup>) between 2002 and 2007 then a steeper decrease from 2007 until the last year of measurement (2011). The decrease was over 15 µg/m<sup>3</sup>. This is offset by a year long stepwise increase in the 5<sup>th</sup> percentile values starting mid 2007. The level of the 5<sup>th</sup> percentile values appears to have stabilized after the increase, but additional years of data would have been needed to confirm the trend. This is impossible since the instrument has been altered to monitor PM<sub>2.5</sub> pollution. There were no changes in Langdale PM<sub>10</sub>.

SO<sub>2</sub> and TRS: There are no significant changes in any percentiles at the Langdale and Squamish stations for SO<sub>2</sub> and TRS. All changes are within 1 ppb or less and have thus been discounted.

## 5.7 Time Variation Plots

After examining the long term trends in detail, we now transition to more closely studying the monthly and daily variations in the airshed's pollutant levels. With time variation plots, we can make more detailed observations about which months have the highest and lowest mean concentrations, determine differences in pollutant patterns during an average week and can observe average daily pollutant patterns. Figure 5-7 is the time variation plot created for Horseshoe Bay's CO, and the charts for the other pollutants are in the appendix, plate E, object E-90 to E-110. Weekly plots are found at the top of each figure, and across the bottom, listed from left to right are the average concentrations over an average day, the average monthly levels, and the average total pollution for each day of the week. Boxes with lighter colouring represent the 95% confidence intervals

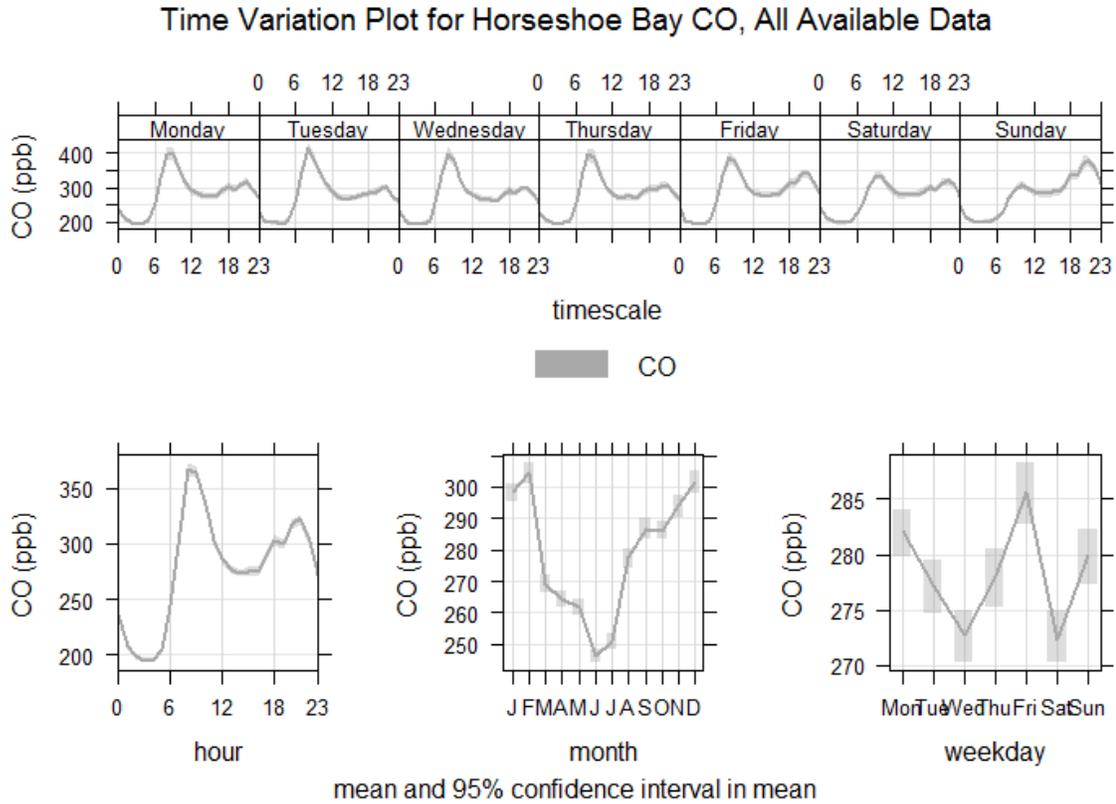


Figure 5-7 Time variation plot for Horseshoe Bay CO; showing daily, weekly and monthly variations'

Data Source: 'Ministry of Environment 2015c'

From the first plot in figure 5-7 we can observe that Monday to Friday show very similar patterns: pollution increases from its daily low just before 6 am and continues rising until its 400 ppb peak at about 8 am. After this point, pollution decreases until noon, after which pollution hovers around 300 ppb until the end of the day. On the other hand, Saturday and Sunday have lower morning peaks, and Sunday's highest peak actually occurs around 10 pm. Overall, (bottom left chart) the daily levels resemble the weekday pattern. Compared to the 150 ppb change between the average daily high and low, the change in total CO emissions is insignificantly small (as seen from the bottom right chart). On a monthly basis, the lowest monthly concentration occurs in June and the highest are December, January and February. When comparing this chart with the daily charts, we can see that the difference between monthly peaks and troughs is smaller than what is seen in an average day. As such, the key CO pollution periods to concentrate upon are primarily daily morning emissions and to a lesser degree the average winter emissions.

The remaining pollutants are detailed in the pollutant subsections below.

NO: The largest change at the Squamish station is a 10 ppb difference between the 4 am low and the 8 to 9 am high on Thursdays (other weekdays are similar, but their peaks are slightly lower). This is marginal to consider as a change, and since the other types of patterns occur on an even smaller scale they should be discounted. Langdale's daily and monthly NO variations are also insignificant since the most extreme change is 5 ppb. Many of Whistler's changes are insignificant as well. The largest change is the 9 ppb difference between the average monthly high in January and the low in May. Overall, average NO concentrations are low throughout

the airshed, and at most what can be observed are small daily variations throughout the Squamish weekdays and the small January peak in Whistler.

NO<sub>2</sub>: All variations at the Squamish and Langdale station take place within a range of 5 ppb and 4 ppb respectively and are therefore insignificant. Whistler's are only slightly higher, with the average monthly being a change of 7 ppb from the peak in January to the low in June. The highest weekday value occurs around 9 pm on Fridays. There is a second smaller peak around 8am. Other weekdays at all the stations across the airshed also have this pattern, although they take place with smaller variation. In sum, there are only very small daily and monthly variations in NO<sub>2</sub> pollution: small variations occur on weekdays and winter has marginally higher concentrations. In terms of the overall significance of this variation, Whistler's is marginally significant at best while Squamish and Langdale are not.

O<sub>3</sub>: Both Squamish and Whistler have pronounced daily changes in O<sub>3</sub>. Levels hover between 14 and 10 ppb throughout the early morning then begin to increase between 6 and 7 am. O<sub>3</sub> peaks between 3 to 4 pm. There are no changes in this daily pattern except that Whistler's daily peak is about 5 ppb higher (25 ppb and Squamish versus 30 ppb at Whistler). Seasonally, ozone is highest in April and May and lowest in October. Whistler's monthly averages are slightly higher. Overall we can conclude that the daily and monthly patterns at the two stations are the same but Whistler has slightly higher O<sub>3</sub> concentrations.

PM<sub>2.5</sub>: No significant variation occurred at Horseshoe Bay since the average values range between 3 µg/m<sup>3</sup>. The Langdale BAM monitor recorded a maximum variation of 5 µg/m<sup>3</sup> seasonally (July is the highest) and 4 µg/m<sup>3</sup> over each daily pattern (there is a small weekly peak in the afternoon). These changes are minimal. The Squamish BAM instrument recorded the highest weekday peak of around 9 µg/m<sup>3</sup> between 10 pm and 2 am on Saturday and low weekday values with changes between only 2 to 3 µg/m<sup>3</sup>. All these average values are again quite low—lending low significance to the changes. Seasonally, the concentrations shift between the March low of 4 µg/m<sup>3</sup> and the August high of almost 9 µg/m<sup>3</sup> (another small change). On the other hand, the TEOM records different patterns. Daily there is only one peak that occurs during the evenings, and this becomes more pronounced until the highest nighttime values on Saturday. There is a small 4 µg/m<sup>3</sup> change between the low in January and the high in July to September. This once again stresses the differences in the values that the two different monitoring instruments record. Whistler BAM records the same evening PM<sub>2.5</sub> peaks as Squamish, but the average concentrations are higher. Saturday evening is also the highest at Whistler. Unlike Squamish, the highest monthly values are in December and the lowest are in June (with a total difference of 5 µg/m<sup>3</sup>). Whistler TEOM records similar daily patterns but the seasonal pattern is different. There is less than a 3 µg/m<sup>3</sup> difference with the lowest value being in June while the highest is in August.

The above results suggest that Squamish and Whistler are the only stations with at least marginally significant results. Further, it is highly likely that the PM<sub>2.5</sub> sources have difference characteristics between the two stations, and also that any management of PM<sub>2.5</sub> emission should be put towards reducing the Friday and Saturday night emissions—particularly in December.

PM<sub>10</sub>: PM<sub>10</sub> changes are most pronounced at the Squamish station compared to Langdale. At Squamish, PM<sub>10</sub> levels are lowest between 4 and 5 am and then climb through the morning. In the afternoon (around 3 pm) they peak at about 20 µg/m<sup>3</sup> and then there is a second slightly lower peak at 9 pm. Over the weekend afternoon levels are low. Seasonally, July has the highest average PM<sub>10</sub> levels while December and January are the lowest. Langdale's maximum PM<sub>10</sub> change is only 5 µg/m<sup>3</sup>. This occurs between the annual low in January (7 µg/m<sup>3</sup>) and

the highest value in September. The highest weekday value is on Thursdays around 6 pm but all other values are within  $3 \mu\text{g}/\text{m}^3$ . Overall, we can say that focus should be on reducing afternoon and evening  $\text{PM}_{10}$  levels, and  $\text{PM}_{10}$  levels during the summer (particularly July). In Langdale, some inquiry could be put into investigating how to reduce levels in the late summer, September and even October.

$\text{SO}_2$ : There is no significant variation in  $\text{SO}_2$  values at the Langdale or Squamish stations. This is because average levels are no higher than 1.5 ppb, while Squamish's are less than 1 ppb. Changes therefore have a maximum 1.5 ppb variation which is insignificant

TRS: All average values at both the Langdale and Squamish stations fall within 0 and 0.7 ppb. All changes are thus insignificant.

## 5.8 Study of Average Hourly Concentrations

After analyzing the long term, seasonal, and daily patterns and their relative significances in great detail, we are still missing an analysis of less cyclical data. In particular, up to this point high values that occur infrequently have been hidden by examining large bodies of data together. This means that short high concentrations such as pollution episodes, or less frequent characteristics have been hidden. Charts that plot the average hourly concentrations of a given pollutant offer a solution to this problem since they show the average hourly concentration of every month of data individually. While data is still somewhat averaged, it is still specific enough to facilitate finer observations. Figure XXX shows the chart made from Horseshoe Bay's CO levels. Every year of data is contained in a box while the concentrations for each month are shown as a horizontal stripe within the boxes. Each box corresponds to one average hour of a given month. Red denotes high concentration while blue is low. Missing data is left uncoloured.

## Average Hourly Concentrations of Horseshoe Bay CO for All Available Data

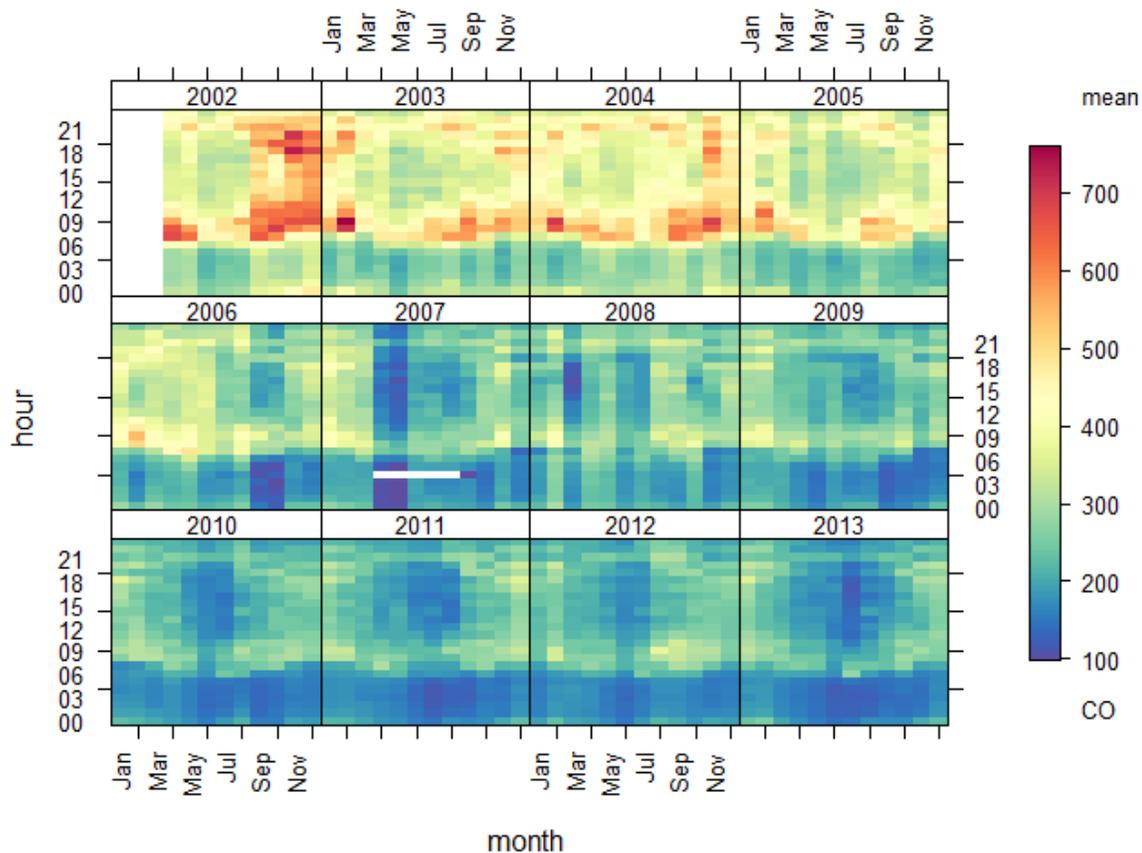


Figure 5-8 'Average daily concentrations for all months of Horseshoe Bay CO measurements'

Data Source: 'Ministry of Environment 2015c'

In order to clarify the previous paragraph, we shall examine figure 5-8. The large patch of red and orange in 2002 communicates that not only was this the highest year of CO, but the highest concentrations occurred during daylight hours between August and December. This pattern of high concentration repeated with decreasing intensity each year until 2005. There also appears to be a recurring several hour peak starting around 9 am in February during 2002 until 2006. Besides these observations, April 2002 contains the highest remaining levels of CO (occurring between 7 and 9 am). From 2007 onwards, no significant episodes of high pollution occur. This echos the small reduction of CO observed in some of the previous steps of the analysis.

The analysis of the other pollutants is elaborated in the subsections below, and the charts can be found in appendix plate E, object E-111 to E-130 and are summarized in the paragraphs below.

NO: Generally Langdale's NO is low. High pollution is short lived—the highest pollution only occurs over one hour. This echos the short residence time that NO has in the atmosphere before it reacts to form different compounds. Similar to what was shown with the time variation plots, most years have a one hour peak during 9 ams and 11 ams in July and

August. The largest amount of high values occurred in the fall of 2002 and 2004 during the morning to early evening. Almost all concentrations in spring are relatively lower.

NO at Squamish is fairly even except for several well defined exceptions. The biggest episode (35 ppb plus) occurred in August and September 2006 around 9 am. September 2005 at 9 am is much lower, and December 2005 around noon takes a distant third. There also appears to be recurring medium pollution events during fall mornings and evenings throughout the years of data.

At Whistler there are also few episodes of high NO. The most notable is a period of over 35 ppb in January 2004 that occurred around 6 pm (concentrations had been medium to high for most of that day). January and February also had one average hour of high concentration around 9am. There are bands of medium range concentrations (10-20 ppb) in the shape of a sine curve that happen consistently every year. This pattern was likely hidden given that it is a daily pattern of medium values that shifts between about 7 am in the summer to 11 am in the winter. There is also a period of mid to mid-high evening NO levels during the winter (between 6pm to midnight). The intensity of both these patterns fades as years progressed.

NO<sub>2</sub>: For Langdale, the most defined pollution occurred in November 2006 around 6pm. Conversely, there was a period of low pollution during the afternoons and evenings in August 2005 and throughout the day in March 2010. Finding out whether there were unique changes during these periods of low and high concentration could isolate emissions sources and potentially yield actions for making reductions.

At Squamish, the highest NO<sub>2</sub> was in January 2008 at 7 pm (17 ppb). This was merely the peak of a larger pattern. During winter, mid to high range values consistently occurred between 8 am and 10pm. With each month closer to the summer, concentrations became marginally lower and migrated to later and earlier times. This means that during winter the mid levels occurred throughout the day but an increasingly large afternoon low developed as summer approached. This pattern occurred to at least some degree every year.

Whistler has one strongly defined period of high NO<sub>2</sub> values: January 2008 contained values of around 15 to almost 30 ppb. This appears to be an isolated incident. Whistler also appears to have the same pattern as Squamish, with increasingly long afternoon lows leading into the summer and a decreasing afternoon gap leading into winter. As a result, there are increasingly longer periods of medium range NO<sub>2</sub> values until the winter solstice and then decreasing values until the summer equinox. This points towards a source associated with darkness and/or NO<sub>2</sub> is being converted into O<sub>3</sub> during daylight.

O<sub>3</sub>: The Squamish average hourly concentration chart is dominated by the seasonal pattern of high spring and summer levels observed in the previous sections of the analysis. Apart from this pattern, there is little deviation. The exception is the accumulation of mid range O<sub>3</sub> concentrations from midnight until 9 am from February to April 2011. Other years occasionally also show these mid-range values but they only last for one month instead of three. Given the pattern, this could simply be the result of climactic conditions—especially since this is mirrored at the Whistler station. Given that the pattern of high O<sub>3</sub> levels fits well into the pattern of low NO<sub>2</sub> levels, it is very possible that the NO<sub>2</sub> pattern is driven by conversion into O<sub>3</sub>.

PM<sub>2.5</sub>: At Horseshoe Bay, the highest PM<sub>2.5</sub> values were present throughout much of 2002. The top values occurred between June and October and tended to fall between 6 am and 4 pm. This period of higher values also appeared annually but with decreasing intensity until

2006. It also reappeared in 2009. Besides these periods, August 2010 and June to August 2009 stood out from the rest of the data with their mid to high values. Given the lack of repetition, the conditions and sources behind these periods could be non-periodic events such as wildfires.

Over the two years of PM<sub>2.5</sub> BAM monitoring at Langdale, there were only two instances of the highest readings (around 18 µg/m<sup>3</sup>). This was between 7 and 9 am during June and August 2013. Generally readings during those months appear slightly higher than other months—especially between the morning and early evening.

By far the highest Squamish PM<sub>2.5</sub> BAM readings were during August 2010. Readings peaked around 16 µg/m<sup>3</sup> between 9 am and noon. The summer of 2013 also had a series of mid to high range values during the morning. Further, fall pollution levels between 2010 and 2013 may be increasing during the evenings—although another year or two of data are necessary to confirm whether this is indeed a trend. Conversely, the Squamish TEOM instrument measured mid to high readings during summer evenings instead of fall. That being said, there are only two years out of three that observations can be made since 2013 is missing data during this critical period.

The Whistler PM<sub>2.5</sub> BAM instrument recorded evening and early morning mid to high range concentrations of PM<sub>2.5</sub> (of 10 µg/m<sup>3</sup> and over) between fall and early spring. Besides this, there is only one other instance of higher values: between 9 am and noon during August. As such, there appears to be weak seasonality in Whistler with one non-periodic summer incident. The TEOM instrument also recorded the seasonal pattern and the isolated summer incident. Additionally, it also picked up the same sinusoidal morning curve throughout each year (just like the NO and NO<sub>2</sub> readings. This means that mid level concentrations tend to happen just past 9 am in the winter and shift earlier towards the summer. At the moment the pattern does not appear to be getting stronger and stays under 10 µg/m<sup>3</sup> so it is of low priority to address compared to the evening episodes.

PM<sub>10</sub>: The Langdale PM<sub>10</sub> BAM monitor also registered the same morning sinusoidal curve. There was also a second curve of equal intensity in the evening. The bottom curve shows the same shift to early morning then trends slowly later towards the solstice. The upper curve shows mid-range values around 9 pm trending earlier towards the solstice. All peaks of upper range values occur over only one hour and fall along either the upper or lower curve. These details point towards the main seasonal and peak episode source being the same and likely associated with daybreak and dusk activities.

On the other hand, the Squamish PM<sub>10</sub> pattern is very different. Levels are mid to high during daylight hours with a peak occurring around 3 pm and a secondary one at 9 pm between June and August. This pattern appeared to fade out over the last three years of study. The highest registered instance of PM<sub>10</sub> pollution was around 45 µg/m<sup>3</sup> and occurred in September 2006. Most hours during September were also fairly high and this is not reflected during the other years of measurements.

SO<sub>2</sub>: Langdale SO<sub>2</sub> also shows a sinusoidal morning curve. All of the top SO<sub>2</sub> values (3.5 ppb or less) fall along this curve except for during the early morning in September. It also appears that concentrations have gained at most 1.5 ppb from 2006 onwards.

Background SO<sub>2</sub> levels at Squamish also appear to have been increasing from 2006 onwards—pointing to a potential increase in regional background levels. On the other hand, peaks in SO<sub>2</sub> decreased after 2006 (within 9 am and 9 pm during the summer months). That

being said, the highest concentration shown on this chart is 2.5 ppb—making such changes marginal at best.

TRS: Langdale TRS also shows a subtle morning mid-value sinusoidal curve (once again shifting earlier in the summer). There are only two main TRS incidents where values were 2 ppb or higher: throughout the early morning (before 9 am) during July 2011 and between 7 and 8am on June 2013.

Levels of background TRS at Squamish appeared to have gained 0.5 ppb across all hours of all months after June 2009. 0.5 ppb is an insignificant change because this is smaller than the instrument's precision (G. Veale, personal correspondence May 14<sup>th</sup> 2015). The highest concentrations all occurred during the evening of April, July and September 2004.

## 5.9 Pollution Roses

Thus far we have discussed pollution levels but there has been no discussion about trends in the direction from whence pollutants originate. This section addresses this gap using an analysis of pollution roses. For each station's pollutant, there are two variations of pollution roses: one plotting annual roses and the other with seasonal roses. The pollution roses created for this study plot the average pollution level at various directions and windspeeds and this is set on a compass plot. Unfortunately few charts could be made because there were only several stations with both MET stations and pollution measurements: Horseshoe Bay, Langdale, and Squamish. Squamish had to be discounted since this study found that the wind direction measurements were inaccurate for at least between 2002 and 2013. This leaves us with the capability to discuss the direction of pollutants for only a small part of the airshed—making it much more difficult to trace sources and design responses.

The Horseshoe Bay charts are shown and described below (figure 5-9) as an example of how such visualizations can focus our information about the highest levels of pollution. The pollution roses for the other pollutants are discussed in the subsections that follow the discussion of the Horseshoe Bay charts. All remaining charts are located in the appendix plate E, object E-131 to E-142.

### Annual Pollution Rose for Horseshoe Bay CO

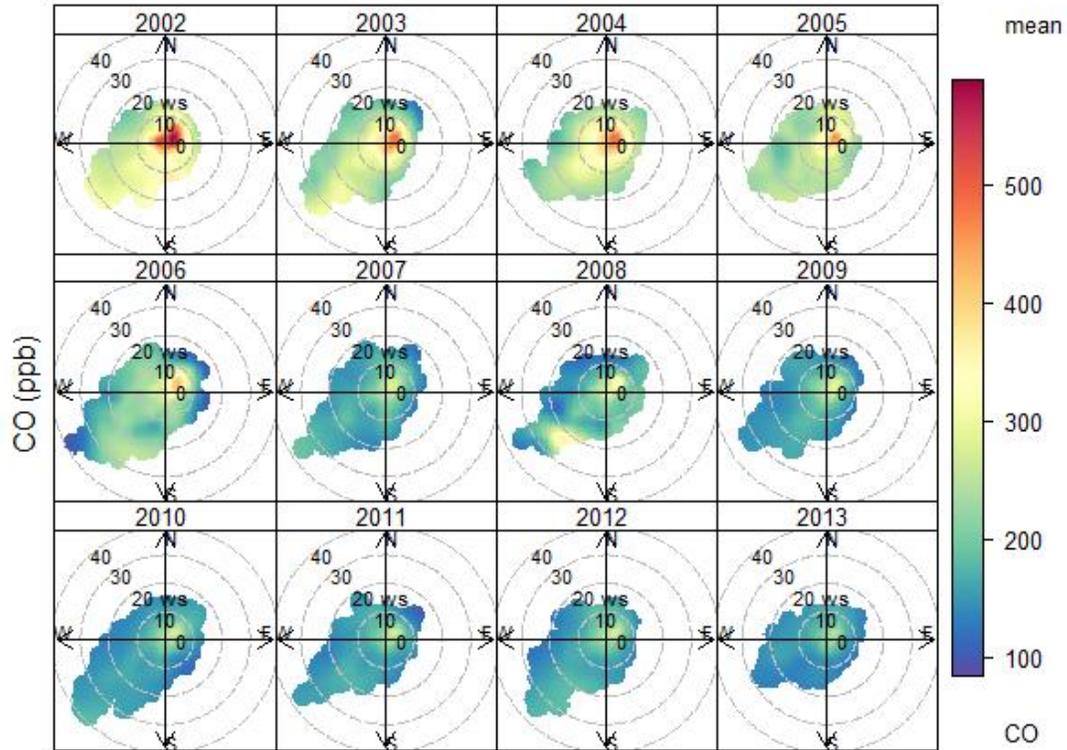


Figure 5-9 'Annual pollution roses for each year of Horseshoe Bay CO measurements'

Data Source: 'Ministry of Environment 2015c'

The first observation we can make about figure 5-9, is that the red coloured high CO values are concentrated in the plot area that is under 10 km/h. Since the pollution occurs in equal directions around the station, we can add that this pollution likely comes from a diffuse source near the monitoring station which then builds up during calm winds. As the years progress, this pattern remains but its intensity fades until it is barely discernable in the latter years of study.

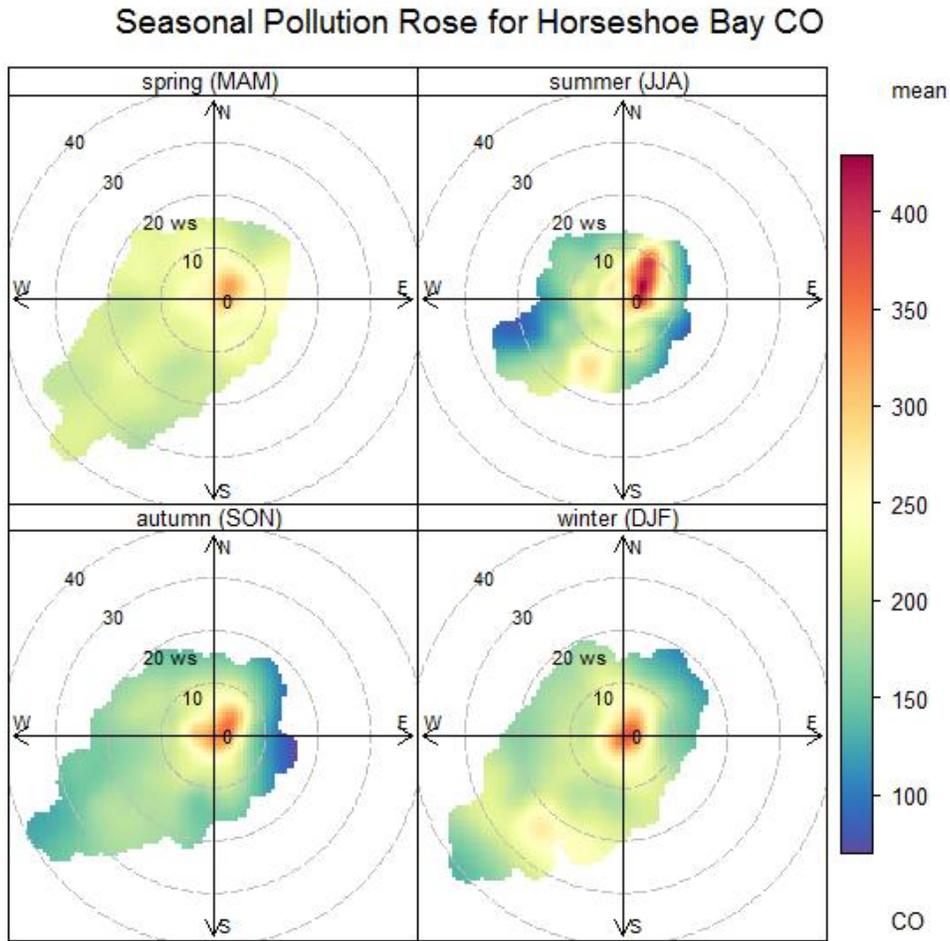


Figure 5-10 ‘Seasonal pollution roses for Horseshoe Bay CO, 2002-2013’

Data Source: ‘Ministry of Environment 2015c’

According to figure 5-10 we can see that this nearby diffuse source remains throughout the seasons. Its intensity does vary though, and appears strongest in summer with the most intensity coming from the north-eastern direction. In spring and winter there is also a lesser, more distant source in the south-western direction. The spring pollution rose has less intense levels during calms but has higher background levels from all directions and speeds compared to the other seasons. Since CO builds up during calms, and generally builds up evenly from all directions, CO mainly comes from nearby diffuse sources—likely the nearby highway and community traffic.

NO: Most of Langdale’s pollution also comes from very close to the station, from the south-east. There is a second source with mid-range measurements (around 4 ppb) further away to the south-east. This pattern is consistent across the seasons with spring having the greatest intensity of close proximity emissions.

NO<sub>2</sub>: Each year most NO<sub>2</sub> comes from the south-east and a secondary body of lower intensity pollution comes from the opposite direction. There is also a mid to low level source in the south-west. Pollution from the south-east generally comes with wind between 5 to 10 km/h. Levels fade as the wind speed drops then increases again during calms. This points to a

local source in the area whose emissions accumulate during calm conditions. The annual windroses also indicate three slightly more distant sources (the largest in the south-east, a mid to high source in the north-northwest and a mid to low level source in the south-west) that have their pollution transported to the station by low wind speeds. Seasonally, the only change to this pattern is in spring when mid levels are transported to the station by low winds (5 km/h or less) from the north-east.

PM<sub>2.5</sub>: The major pollution pattern recorded at Horseshoe Bay PM<sub>2.5</sub> (TEOM) was high range measurements (up to 8 µg/m<sup>3</sup>) mainly coming from the south-west. This was transported by a range in windspeeds, from calm conditions up to 15 km/h. A small portion also comes from all directions under 5 km/h. Likely, there is a local source emitting PM<sub>2.5</sub> which builds up during calms and also key sources that emit in the south-west at various distances from the station. There is some seasonal variation (being at most 5 µg/m<sup>3</sup>). Summer brings the highest local and semi-local emissions, followed by autumn, spring and winter.

Langdale only contains just over two years of PM<sub>2.5</sub> monitoring so it is too short to define a trend. From the preliminary information, pollution may originate from a local and semi-local source to the south-west. There also appears to be some mid-level PM<sub>2.5</sub> values from the north-east. Seasonally, summer appears to contain the most intense levels during calm winds and also during winds up to 10 km/h in the south to south-western and north-eastern direction. Autumn, spring and winter also reflect this pattern but with decreasing intensity.

Further years will need to be analyzed in the future in order to verify whether these observations hold true.

PM<sub>10</sub>: Once again there is a concentration of high range emissions (around 15 µg/m<sup>3</sup>) during calm winds, indicating a local source at Langdale. An accumulation of varying intensity occurs for each year that PM<sub>10</sub> was monitored. All years also have a mid to high range concentration transported from the south-west with winds around 5 km/h. Most years there are also mid to high range concentrations brought with south-east with winds around 10 km/h or higher. Further, about half the years also have a mid-range concentration of PM<sub>10</sub> from the north-east brought with 5 to 10 km/h winds. In 2008 there was an anomaly where 15 µg/m<sup>3</sup> emissions were also transported past the monitoring station by winds over 10 km/h from the west. As we can see, there appears to be a number of well defined PM<sub>10</sub> sources that are both local and transported.

Seasonally, these sources appear to change. Summer has the highest concentrations (18 µg/m<sup>3</sup> versus 14.5 µg/m<sup>3</sup>). While 2008 showed high range concentration from the west as an annual anomaly, this is shown as a consistent trend in the summer. Summer also shows mid to high concentrations spanning from the west to the east transported with low winds (less than 5 km/h). Summer spring and autumn all have mid concentrations during calms and also from the south-west with winds around 5 km/h. All seasons also have mid range emissions between 5 and 15 km/h from the south-east.

SO<sub>2</sub>: Since SO<sub>2</sub> levels are low, it is difficult to differentiate significant patterns. At Langdale, the main pollution pattern is mid (1.5 ppb) and high range (2.8 ppb) levels concentrated during calm winds, and between 0 to 10 km/h from the north. There is also some mid-range levels between 5 to 10 km/h from the south-east and a smaller accumulation to the south-west. The north and south-east concentrations become about 1 to 2 ppb more intense after 2007.

From these observations, we can summarize Langdale SO<sub>2</sub> concentrations are mainly coming from the north during low winds with a slight accumulation during calms. Small additions may be transported from other directions. Patterns remain consistent throughout the seasons although summer and autumn show marginally higher emissions from the south-west compared to the other seasons. Overall, the key source appears to come from the north but levels are not very high even from this contribution.

TRS: TRS at Langdale mainly comes from the north between 0 to 8 km/h. There is also a lower intensity source to the south-east between 5 and 10 km/h. Summer appears to lack this lower intensity pattern.

## **6 Discussion**

When first exploring the potential for conducting this thesis, the author's search yielded several basic pieces of information. Firstly, there was a lengthy research gap where no studies had been completed throughout the Sea-to-Sky Airshed. Secondly, the Airshed was generally thought to be quite clean and thus studies were of low priority. Thirdly, there existed ample archived raw air quality data collected by the BC government. When viewed together, a picture emerged where (should the data be adequate) a study could not only address the research gap but could be used to inform the monitoring and management that had been ongoing throughout this research gap. In fact, the management system itself had been designed without comprehensive recent information, so there was potential for science-based improvements.

After further investigating the research gap and the reasons behind its existence (discussed in the problem definition), the next step was to investigate whether the years of collected air quality and MET data could support an analysis aimed at informing the airshed management. Indeed, this became the first research question of this study.

In order to address this question, data was downloaded in January 2015 and then visually inspected. The period of time for familiarization with parameters, units and the purposes of the parameters took a deceptively long—largely due to the lack of online guidance to aid with interpretation of data downloaded from the government database (e.g. many category titles were jargon for casual users). This runs counter to the premise of having the data publically accessible online. Further, unclear station labelling made it appear as though more stations existed than in actuality. Clarifying the inconsistencies subsequently created, was also time consuming (for example, the discovery of what appeared to be two Squamish MET stations, was actually the same station and analyzers, only with a new data logging system).

In order to establish a background about the network structure, and insight into how the data was collected, a tour of the airshed's monitoring network was organized with the BC MoE's Sea-to-Sky airshed technician. This visit was not only critical for clarifying the physical structure of the monitoring network (especially given the online database), but also for learning the policies and operating procedures that govern the process of drawing outdoor air into the analyzers to the data appearing on the database. Employee safety policies, monitoring station siting rules, and calibration procedures were also covered. Without the station visit, the author would not have had enough background to design the method, to problem solve when issues arose, nor to shape as detailed a set of recommendations.

Subsequently, an overview of stations, analyzers, years of collected data, annual data collection and boxplots was completed for both the MET and contaminant measurements to conceptualize the monitoring network data. The completion of this overview was important in identifying that different parameters were monitored over different time periods at each of the stations. Some, such as Langdale PM<sub>2.5</sub> had too few years to qualify for long term trend analysis. Others, like Squamish's 2002 and 2003 O<sub>3</sub> measurements were missing data throughout periods of high concentration. The overview also identified that the mobile Whistler Function Junction station recorded only two months of patchy data, and could therefore not be used in most operations. This constitutes a lost opportunity and wasted resources, since the station was explicitly deployed and positioned to record the impact of the 2010 Vancouver Olympics on the airshed's ambient air quality (G. Veale personal

correspondance March 15<sup>th</sup> 2015. At most, the data from this station supports a daily and weekly analysis with little to contextualize its outcomes.

The network overview also yielded the observation that during the station commissioning year, data collection was typically low. The first full year of Horseshoe Bay data collection was thus an anomaly. Upon discussion with Graham Veale, it was discovered that the provincial government database was incomplete, and that years of CO, PM<sub>2.5</sub> and MET data had not been uploaded. Without these additional years of data, long term analysis would not have been possible at the Horseshoe Bay station.

After identifying these preliminary issues, the author used station summary plots, boxplots and histograms to inspect the data quality. MET data was found to be of lower quality than the contaminant data. According to Graham Veale, this is because contaminant data earns more QA/QC, as it is used more frequently for reporting (such as by the BC Lung Association) (G. Veale personal correspondance March 19<sup>th</sup>). Anomalies in boxplots revealed some inaccurate temperature and humidity measurements at the Port Mellon MET station; upon advising Graham Veale, he and the airshed technician further analyzed the data. Ultimately, it was determined that since the Port Mellon MET station was administered by industry instead of the BC government (and thus did not undergo the governmental QA/QCing procedure) all this data would be discarded from the study. Discarding an entire station worth of data, not only represents the loss of one station from the analysis, but it is also a significant waste of resources. Creating policy that mandates governmental QA/QCing procedure and regular station audits would thus ensure standardized data quality. This is especially important for supporting future studies such as dispersion analyses which rely on ample MET data. Over a year of inaccurate Squamish humidity measurements was also removed from the government database.

Despite issues with data clarity, completeness and quality, there still remained sufficient years of data, pollutants and stations to perform an analysis. Before this could be completed, it was first necessary to gain insight into the components and approaches of ambient air quality reporting and to develop a background about the airshed management and the Sea-to-Sky Airshed.

A literature analysis was conducted to locate guidance for analyzing and interpreting large volumes of air quality data for management and policy. While it did not locate such guidance, it was able to identify basic reporting components across air quality reports, as well as new ideas for approaching and communicating long-term ambient air quality data.

In turn, the findings from the literature analysis created the foundation for the author's method of analyzing and interpreting pollution trends and characteristics. This was combined with guidance from Graham Veale, study of the R OpenAir user manual, and input from one of the professors from Quest University Canada. Caution is recommended against uncritically applying this method, since it is designed for long term studies. Different components would be present for annual reports. Further, this airshed contains little recent background and so consists of steps to develop such knowledge. Studies of airsheds containing more information may be able to reference instead of develop such information from scratch. Furthermore, airshed managers or seasoned consultant may need to develop less background knowledge.

During the process of establishing the MET background, the author identified further issues with the MET data. When plotting pollution roses and comparing them to the previous report, the author found that the Squamish wind direction measurements were inaccurate

since mid 2001 to present. At the time of writing, the airshed manager and technician from the BC MoE had been informed of the issue and were in the process of determining the full period of inaccurate measurements, whether this affects any old reports, and whether the information can be corrected. This finding is significant because this represents over 13 years where, by the author's calculations all wind directions were shifted by 45° counterclockwise. Since the analyzer was still recording inaccurate measurements, this would affect not only studies using the same information as this thesis, but also studies using future measurements.

Should the measurements be unable to be corrected, there will be even sparser MET information for mapping pollution transport throughout the airshed. As it stands, there are only five stations with wind measurements throughout the airshed. Port Mellon and Squamish are currently discounted, and the Whistler Function Junction station recorded only 2 months of data so is of little use. This leaves only 2 stations for the entire airshed. This data alone is not enough for understanding how pollution enters, exits and moves throughout the airshed.

### **Reflections Regarding Ambient Air Quality:**

Conducting the 9 analytical steps (chapter 5) resulted in an overabundance of observations about the airshed's contaminants. On the one hand, this demonstrates that the operations were effective and that the ambient air quality data could indeed yield information about trends and characteristics; but on the other, there are too many to communicate as is to a manager or policy maker. To enhance the quality of the findings it is necessary add a system of filtering.

Since the management of ambient air quality throughout Canada is guided by a variety of ambient air quality objectives, and since these objectives are set based on impact to human health, quality of life (eg visual air quality and nuisance), infrastructure, and ecosystem health; it follows that these objectives can be used as benchmarks for evaluating the significance of the characteristics and trends identified in chapter 5. The author suggests a short set of criteria for extracting information that is relevant to managers and policy makers from the analysis:

1. The number of exceedances
2. The degree that annual contaminants levels approach objectives
3. The severity of the consequences of having exceedances or near exceedances
4. Trends in contaminant levels relative to exceedances

Based on these criteria, we can focus the observations from the analysis into the following summaries:

**CO:** CO is only measured at one location (Horseshoe Bay) located near the southern border of the airshed. At this location, CO levels fall well below the 1 hour and 8 hour PCO. Most of the readings range between 70 and 410 ppb, with none exceeding 2500 ppb. Between 2002 and 2013 CO levels have declined by about 200 ppb, and the decline has been more pronounced in the higher values between 2003 and 2008. Effects other than long term changes and seasonal variation exert the majority of influence on CO levels. Daily patterns likely play a major role, and CO levels typically fluctuate more than 200 ppb each weekday (Monday to Friday). On these days, levels peak between 8 and 9 am. Over the weekend, the morning peak is smaller, dropping slightly with afternoon traffic then picking up to equal or greater levels between 7 and 9 pm. Average daily concentrations change little over each week. There is also a seasonal pattern, but the change (50 ppb) is less than what is seen over each day. December to February comprise the highest months. CO builds up during calms. During the summer and winter there are also concentrations between 250 to 300 ppb that are

transported by medium winds from the south-west. During summer, at least, medium level wind mainly transports CO. Overall, CO is not well measured across the airshed, but considering the measurements gathered from the Horseshoe Bay station, the state of this contaminant is of lower importance. Levels are always well below the limit, and moreover, they have decreased marginally over the course of the study.

**NO:** ANY does not have federal, provincial or municipal objectives for comparison. It is thus difficult to summarize the findings and to comment on their significance. None-the-less, an attempt will still be made, especially since this contaminant leads to other secondary contaminants within the airshed—in particular O<sub>3</sub>. NO is monitored at 3 stations and also at the mobile Whistler Function Junction station. Data capture is generally high, except for during late 2007 at the Whistler Meadow Park station. On average, NO levels are low. Most range between 0 and 11 ppb and at Langdale the range is half. No measurements are larger than 163 ppb. NO levels can affect subsequent NO readings for up to a day at Squamish and Whistler, which is inconsistent with the pollutant's typically fast reaction time. Langdale has shorter retention. The largest long term decline in NO is at Whistler, with the highest readings experiencing the largest decrease. Overall, the long term trend equals the average daily fluctuation in NO, but is still significant relative to the typical range in NO's measurements. NO is lowest around 4 am and highest around 8 to 9 am. Whistler also shows a 9 ppb difference between its monthly high in January and low in May. All other changes are insignificant. Any periods of NO's highest recorded values only lasted one hour (before likely reacting to form other pollutants). NO levels reduce during daylight hours as they presumably react. There is only information about the direction of NO levels in Langdale. At this station, levels are high during calm weather. There is also a lesser concentration in the south-west.

Overall, NO levels are low and are of low priority throughout the airshed. Any changes are within 10 ppb and are thus very small. They are mentioned only because of their size relative to the range in the majority of NO readings. There are no long term changes except for a slight reduction in Whistler's highest recordings.

**NO<sub>2</sub>:** NO<sub>2</sub> is measured at the same stations as NO and has the same data collection. NO<sub>2</sub> does not exceed the Interim Provincial AQO and in fact most calculations hover around 1/4<sup>th</sup> of the objectives. Generally, most pollution falls between 0 and 17 ppb, with the all-time highest reading being 58 ppb. NO<sub>2</sub> levels tend to affect subsequent readings for up to a day and a half, with Langdale being shorter than the other stations. The remainder (anything other than long term changes and seasonality) and seasonality dictate NO<sub>2</sub>'s levels throughout the airshed. No long term trends except for a marginal reduction (about 8 ppb) in Whistler's upper and mid NO<sub>2</sub> readings are detected. Whistler has marginal (7 ppb) seasonality—January is the peak while June is the lowest. Whistler also has a marginal weekly pattern-- the highest average weekly reading is on Fridays around 9 pm. All other stations have similar patterns, but since they occur with even less variance, they are insignificant. There are generally lower NO<sub>2</sub> readings during daylight hours, corresponding to a portion being converted to other compounds such as O<sub>3</sub>. Once again, there is information about the direction of NO<sub>2</sub> pollution only from the Langdale station. At this station, the highest readings come from the south-east during low winds, and accumulations occurred during calms.

On the whole, NO<sub>2</sub> levels across the airshed are not of great importance since they are low compared to all objectives and furthermore, they are not increasing. Whistler shows a very marginal downwards trend, as well as marginal monthly and weekly patterns. While the monthly and weekly patterns are also reflected at the other stations, they have little variance and thus little significance.

**O<sub>3</sub>:** O<sub>3</sub> is monitored at Squamish and Whistler. While average levels are higher at Whistler, Squamish's surpassed the 1 hour NAAQO Maximum Acceptable Level 3 times in 2009. Both Squamish's and Whistler's readings hover within 13 ppb of the 8 hour CAAQS throughout the study period. O<sub>3</sub> measurements at Whistler typically fall within 0 to 63 ppb and Squamish's between 0 and 51 ppb. The highest recorded measurement was 88.4 ppb at Squamish. Once again, Squamish is most affected by the remainder (all effects other than seasonality and long term trends), followed by seasonality. Part of the remainder is accounted for by daily variation in O<sub>3</sub> levels. O<sub>3</sub> has the most pronounced daily variation out of all the airshed's pollutants, and levels peak between 3 and 4 pm. Ozone measurements affect subsequent measurements up to half a day, with decreasing influence. Levels are higher during daylight, reflecting that sunlight drives the formation of O<sub>3</sub>. Seasonally, ozone is highest in April and May and lowest in October.

Managing O<sub>3</sub> throughout the airshed is of high importance. While annual levels do not appear to increase over the study period, O<sub>3</sub> levels fall consistently close to the objective. Given the multitude and severity of O<sub>3</sub>'s effects, it is of utmost priority to reduce levels. Since levels are highest during spring afternoons, targeting morning to noon precursor pollutants (pollutants that react to form O<sub>3</sub>) would position the reduction during the build-up and peak of O<sub>3</sub> levels.

**PM<sub>2.5</sub>:** PM<sub>2.5</sub> is monitored with 6 analyzers at 4 stations and at the mobile Whistler Function Junction station. Two of the analyzers are TEOM while the rest are BAM. As mentioned in earlier chapters, BAM analyzers are known to trap more PM<sub>2.5</sub> components and thus show higher readings than TEOM. Some of the analytical operations also found that the two types of analyzers recorded different pollution patterns. Considering that other airsheds across the province are switching to BAM, (BC Lung Association 2014), this has wider reaching implications than simply for this study and airshed.

PM<sub>2.5</sub> should be a management focus at all stations since levels approached the annual Provincial AQO. Whistler PM<sub>2.5</sub> came the closest to the objective. After this occurred in 2010, annual levels appeared to drop. Several more years are needed to confirm whether this is indeed a trend. Horseshoe Bay had the lowest levels out of all the stations and therefore reducing levels at this station are afforded less priority than Whistler, Squamish and Langdale. Most PM<sub>2.5</sub> concentrations fall between 0 and 15 µg/m<sup>3</sup>. The highest PM<sub>2.5</sub> reading in the airshed was 157 µg/m<sup>3</sup> at the Whistler BAM analyzer. Whistler shows a slightly higher range and variation in its PM<sub>2.5</sub> levels compared to the other stations. Overall, PM<sub>2.5</sub> readings appear to affect subsequent readings for up to 2 or 2.5 days, with decreasing influence as time passes. This is the highest for all pollutants and is of significance in complicating identification of sources; also, high pollution incidents have the potential for lasting longer than with other contaminants. Stochastic events and patterns shorter than seasonal cycles account for PM<sub>2.5</sub>'s variance. The largest variance occurs on Saturdays in Whistler, where levels move from their low at 5 pm to their high around midnight - after which point levels decrease through the night. Other days echo this pattern, but with lower peaks. Squamish's highest weekday concentration is also at midnight on Saturdays. The rest of the days show double peaks of around 7 µg/m<sup>3</sup> in the late morning and around midnight. Only Langdale shows a peak of around 8 µg/m<sup>3</sup> in the afternoon. Seasonally, there is a change of approximately 5 µg/m<sup>3</sup> at Whistler, Squamish and Langdale. At Whistler, the highest month is December and Squamish's and Langdale's is July through September. In terms of inconsistent PM<sub>2.5</sub> events, all stations contained some high values in August—likely the result of forest fires. Whistler also had some events between fall and early spring. During the spring, at least, these could be from airborne dust from the gravel used on the roads over the winter (used to manage ice and snow).

From the above summary, the key place to concentrate management resources, first and foremost are Saturday night PM<sub>2.5</sub> peaks in Whistler and Squamish. Considering the timing, the source is likely from wood combustion stoves and fireplaces. Other evenings in Whistler are also high, and could use the same approach. In Squamish and Langdale, there are late morning and afternoon peaks of what could be secondary PM<sub>2.5</sub> formation from other contaminants. Further study is needed for isolating the exact causes to plot a focused response. Other PM<sub>2.5</sub> issues are likely from spring road dust and summer forest fires. There is far less potential to control these sources.

**PM<sub>10</sub>:** PM<sub>10</sub> was measured at Langdale and Squamish, although monitoring was discontinued in early 2011 at Squamish. There were 2 exceedances of the 24 hour Provincial AQO in Squamish during 2010. The majority of Langdale's measurements fell under 22 µg/m<sup>3</sup> while Squamish's extended almost double. This brings the upper range of Squamish's typical measurements close to the objective. The highest recorded PM<sub>10</sub> value was 249 µg/m<sup>3</sup> at Langdale. High hourly levels are still an issue though because PM<sub>10</sub> measurements have the potential to influence other measurements for up to 2 days. Generally, levels are most affected by stochastic events and patterns up to and including a seasonal period. There are no longterm changes, but Squamish did show some movement in its lower and upper value measurements. These could not be confirmed, since monitoring was halted. The discontinuation of monitoring creates uncertainty about the nature of Squamish's levels after this point. Squamish experiences seasonal and daily changes of up to 10 µg/m<sup>3</sup> while Langdale's are half the amount. Squamish's levels peak in July and August and each weekday between 8 am and 9 pm. Saturday and Sundays are only highest around 9 pm.

PM<sub>10</sub> in Squamish is of high priority due to its exceedances and level relative to the objective. Generally, reducing PM<sub>10</sub> between 8 am and 9 pm on summer days will target the highest levels. Since patterns do not point to likely sources, recommending specific management approaches is not possible without further study of key PM<sub>10</sub> sources. Furthermore, resuming PM<sub>10</sub> monitoring is necessary, given the exceedance that occurred during the last full year of monitoring and also since there was some movement in the pollutant's low and high measurements.

**SO<sub>2</sub>:** SO<sub>2</sub> is measured at Langdale and Squamish and the mobile Whistler Function Junction stations. All levels are consistently lower than 1/7<sup>th</sup> of the 1 hour Interim Provincial AQO (75 ppb). The mobile Whistler Function Junction station had much lower readings than the other stations. At Langdale and Squamish, the majority of SO<sub>2</sub> data falls under 2.5 ppb. SO<sub>2</sub> exhibits no long term or seasonal trends and insignificant daily fluctuations. All in all, dedicating management resources to SO<sub>2</sub> is of low priority since levels are low and have not increased for the duration of the study.

**TRS:** TRS is measured only at the Langdale and Squamish stations. With 219 exceedances of the 1 hour PCO and 37 exceedances of the 24 hour PCO, this contaminant experienced the most exceedances out of all the other contaminants combined. The majority of the exceedances were at Langdale. While this is indeed a high amount of exceedances, the objective was established primarily to deter nuisance odors. Levels at the stations are not high enough to give cause for health concerns because TRS primarily ranges between 0 and 1.5 ppb. The highest reading was 35 ppb, recorded at Squamish. TRS levels can affect readings up to 24 hours later, although their affect weakens with time. All TRS changes are below 2 ppb and therefore were deemed to be insignificant, since discussing such changes surpasses the analyzer's precision. A pollution rose could only be made for Langdale, and according to this plot, most TRS originates from the north between 0 to 8 km/h. There is also a lower intensity source from the south-east during low winds.

On the whole, TRS is of mid-priority. Although TRS contains many exceedances, priority was downgraded, given that nuisance is the major impact. Nevertheless, strong odour impacts quality of life and causes public complaints, so effort should be allocated to reducing levels. The various analyses yielded little information for targeting contaminant hotspots. This should not impact the management response since most TRS (especially at Langdale) almost certainly comes from the Howe Sound Pulp and Paper mill. Management of this point source is the domain of the BC Government. It is possible to work through the venting logs to troubleshoot the emissions.

### **Reflections on Ambient Air Quality Analysis Method**

The above summaries indicate that not only could the BC MoE ambient air quality data be used for making observations about trends and characteristics, but also that the method developed by the author can communicate the data into an outcome usable by managers and policy makers. Indeed, should this be repeated in the future, the 9-step analytical process and the filtering criteria could be combined to streamline interpretation. For public reports, there can also be less focus allocated to boxplots, histograms, and autocorrelation, since these are largely for establishing a statistical base. Future summaries could also introduce more ecosystem-based standards to create a filtering criteria that is not as biased towards human health. However, these additions can create difficulties since there are no such commonly used standards throughout the province—if not throughout Canada. There would thus be the need to ensure first that the objective would be accepted and valued by the managers and policy makers.

Typically, performing the series of analytical operations such as these takes significant time. Using the open source R software instead of Microsoft Excel (which is currently the norm at the BC MoE) resulted in a significant time savings for the author. In fact, without this software and its OpenAir package, the author would not have been able to complete as many analytical steps and indeed, some would have been impossible with Microsoft Excel. Moreover, should similar studies in the airshed be conducted, almost identical code could be used—thereby further reducing time for completing operations and charts. By the author's estimation, using pre-made code could accomplish this task in one week or less—as opposed to the month to two-month process using Excel.

These comments have far-reaching implications for the management of the Sea-to-Sky Airshed. The MoE has but one specialist and technician that together are responsible for duties including but not limited to station administration, data analysis, reporting, regular administration, presentations to stakeholders, providing information for supporting permitting, and some of the data cleaning (G. Veale personal correspondence March 5<sup>th</sup> 2015). At present, funding is limited for subcontracting work, and the employees have little time to complete their various tasks. Data is collected and warehoused. Limited analysis of short-term phenomena occurs, lending limited support to airshed management. It is thus that without monitoring there is no management, but more aptly; monitoring is of no use to management without analysis and interpretation. Otherwise, monitoring becomes an exercise in expending resources for warehousing data while management operates as a parallel process.

Methods that save time on analysis and interpretation offer a solution for bridging the gap between the airshed's monitoring and management. Using R significantly reduces time for conducting an airshed analysis while simultaneously expanding the type of interpretation that is possible. This facilitates regular, more comprehensive information that can support management tasks such as permitting decisions, air quality strategies and plans, monitoring

network design and resource allocation. One can also more quickly adapt the airshed's monitoring and management system as air quality issues evolve.

Using R at the BC MoE for aiding air quality management is not a new concept. Both employees at the ministry who were contacted by the author, recognized the software, and the ministry had offered employees an internal workshop on its use. Additionally, several ministry employees elsewhere in the province have a good enough command of the OpenAir R package to make their own code. The hurdle for implementation once again has been time. This framework within the ministry indicates potential for not only integrating R into the Sea-to-Sky Airshed's management, but also into the management of other airsheds throughout the province—especially were there to be ready-made code templates.

## 7 Conclusion

Without analysis and interpretation, monitoring and management will occur in parallel with each other. This has been the case for at least 10 years at the Sea-to-Sky Airshed in B.C., Canada. This thesis seeks to bridge this gap. Completing the first task of this thesis yielded not only that the ambient air quality data collected between 2002 and 2013 in the Sea-to-Sky Airshed was sufficient for supporting analysis, but also several findings regarding the monitoring network data. The most significant findings were:

- Inaccurate wind direction readings at the Squamish station between 2001 and present.
- 7 missing years of Horseshoe Bay station measurements.
- Over one year of inaccurate humidity data at the Squamish station.
- Inaccurate readings across the Port Mellon MET station measurement parameters

The outcomes of these findings were:

- Work was initiated at BC MoE to determine the cause of inaccurate wind direction readings and to attempt to correct the database
- Ministry located the missing Horseshoe Bay readings in a private database; these were subsequently incorporated into the BC government Envista database
- Removal of the Squamish humidity readings from the database
- Eliminating the Port Mellon station data from this analysis

Generally, the removal of database inaccuracies and more complete station information prevents future studies from analyzing incorrect data, inaccurate enough to affect observations—even those of the most general nature. It is also important for this data to be correct and complete since it can also be used for evaluating permitting and development.

The first research question, *how can we process multiple years of continuous ambient air quality monitoring data in an accessible form for policy makers* yielded a new method:

1. Develop a foundation about airshed, key source characteristics and MET background
2. Conduct a monitoring network tour to gain overview on stations and background on policies, operating procedures and data collection
3. Check data using station summaries, boxplots and histograms
4. Develop an overview of stations and data using station summaries and determine measurements to include or exclude
5. Analyze the air quality readings using station summaries, air quality objectives, boxplots, autocorrelation plots, time series decomposition by Loess, percentile plots, time variation plots, average hourly concentration plots, and pollution roses
6. Extract of key findings using 4 criteria based on ambient air quality objectives

\* Maintain interactions with key stakeholders throughout the process for troubleshooting and information

This method was applied to the Sea-to-Sky ambient air quality readings recorded between 2002 and 2013 and resulted in the contaminant summaries presented in the discussion (chapter 6). The summaries can be further refined into the following overview for managers and policy makers:

Table 7-1 Management and Policy Summary of Sea-to-Sky Contaminants

| Contaminant   | Station       | Exceedances                       | Trend | Hotspots   | Priority   |
|---|---------------|-----------------------------------|-------|--|------------|
| O <sub>3</sub>  | Squamish      | 3                                 | →     | Spring afternoon   | High       |
|   | Whistler      | Just under                        | →     | Spring Afternoon   | High       |
| PM <sub>2.5</sub>   | Langdale      | Just under                        | →     | Mid-day peak   | High       |
|   | Squamish      | Just under                        | →     | Main peak Saturday midnight<br>Second largest peaks are daily at late morning and midnight<br>Marginal July-Sept. Peak | High       |
|   | Whistler      | Just under                        | →     | Midnight peaks, especially on Saturdays<br>Marginal December Peak  | High       |
|   | Horseshoe Bay | Just under, but less than others  | →     | Marginal midnight peaks  | Mid-High   |
| PM <sub>10</sub>  | Langdale      | 0                                 | →     | Insignificant  | Low        |
|   | Squamish      | 2                                 | →     | 8 to 9 pm during summer  | High       |
| TRS   | Langdale      | 238                               | →     | Stochastic events  | Medium     |
|   | Squamish      | 18                                | →     | Stochastic events, TRS originates from North of station during low winds   | Medium-low |
| NO <sub>2</sub>   | Langdale      | 1/4 <sup>th</sup> under objective | →     | Insignificant  | Low        |
|   | Squamish      |                                   | →     | Insignificant  |            |
|   | Whistler      |                                   | ↗     | Marginal January peak<br>Marginal Friday 9 pm peak   |            |
| CO  | Horseshoe Bay | Well under objective              | ↗     | Weekdays between 8 to 9 pm<br>Weekend afternoons and 7 to 9 pm   | Low        |
| SO <sub>2</sub>   | Langdale      | Well under objective              | →     | Insignificant  | Low        |
|   | Squamish      |                                   | →     | Insignificant  |            |
| NO  | Langdale      | No objective, low levels          | →     | Daily peak at 8 to 9 am<br>Levels high during calm wind  | Low        |
|   | Squamish      |                                   | →     | Daily peak at 8 to 9 am  |            |
|   | Whistler      |                                   | ↗     | Daily peak at 8 to 9 am<br>January peak  |            |
| <i>Mobile Whistler Function Junction Station not applicable</i> |               |                                   |       |  |            |

From table 7-1, it can be seen that there are 6 high priority management areas in the airshed, 1 of mid-high importance, 1 of medium importance, 1 of mid-low and the rest of low importance. Most long term contaminant concentrations have experienced no change over the

study period, and only several showed marginal declines. In all cases, the declines were less than the daily or seasonal variation.

Ultimately, monitoring an airshed takes considerable time and expense. This is a type of task that should be done completely or not at all. In other words, unless data is of high quality, high completeness and collected from enough stations, there is no point investing time and resources into establishing and maintaining a network. As we have seen, large periods of data and indeed entire stations worth of data were discarded from the study and removed from the BC Envista air database. This represents significant wasted resources.

Thus, in response to research question 2, *how can identifying key contaminant trends and characteristics improve the airshed's monitoring in a way that aids management and optimizes resources*, we can reflect upon the findings from table 7-1 and observations made while applying the methodology to create the following monitoring recommendations:

- Add MET monitoring to the Whistler station. The lack of information undermines management responses (particularly of PM<sub>2.5</sub>) since concrete sources cannot be identified, and in fact, one cannot even state the basic direction of origin.
- PM<sub>10</sub> monitoring needs to be resumed because there were 3 exceedances the year before monitoring stopped. Moreover, there appears to be the beginning of an upwards trend in PM<sub>10</sub>'s lowest readings, indicating a possible growth in everyday emissions. Measurement stopped before this trend could be confirmed.
- When implementing mobile monitoring stations such as the mobile Whistler Junction station, ensure that the monitoring performed matches the monitoring objective. Otherwise, resources are wasted when the data cannot support outcomes for the objective.
- Institute QA/QC policy on industry administered stations so that data is not thrown out of studies based on unreliable readings. Station audits and calibration policy would also boost legitimacy. Ultimately, these actions should reduce wasted resources and improve the data network.
- Run several basic operations for data checks once per month. With R coding templates this process should take several hours at most. This will ensure that data within the database is of higher quality, that inaccurate measurements are not recorded for months (or years!), should simplify troubleshooting when problems arise, and finally, should decrease time spent by ministry staff when completing the annual data QA/QC .
- Perform more regular instrument calibration. This can be ensured by checking that technicians follow ministry calibration guidelines. More regular calibration prevents issues such as 14 years plus of inaccurate Squamish wind direction readings, and the resulting work spent attempting to salvage the readings.

To further elaborate on research question 2 and in response to research question 3 (*how can the analysis findings make the current management system more efficient and effective*), a list of recommendations targeting airshed management is presented:

- O<sub>3</sub>, PM<sub>2.5</sub> and Squamish PM<sub>10</sub> should be the focus of management efforts since levels exceed or approach ambient air quality objectives. TRS is of medium priority.
- Re-allocate time and resources from low priority areas identified in table 7-1 to the high priority areas. Re-aligning air quality strategy within the ministry and Sea-to-Sky Clean Air Society could drive such a process.

- Since the Howe Sound Pulp and Paper mill has been identified in the past as the main source of TRS in Langdale, obtaining the emissions logs can verify if they are still the source. Working with the mill to reduce emissions, or implementing permits or fines are all methods for the BC MoE to address this issue.
- Use R and R's OpenAir package for data analysis. This software completes operations and graphs in a fraction of the time as Microsoft Excel (which is currently used). Creating code templates is the most time consuming part of the process, and also requires greater knowledge of R. Contracting out this task, or dedicating in-house personnel would address this issue. Running the code requires only basic knowledge—knowledge which could be learned in one workshop. After implementing such a system, several technicians would be necessary for troubleshooting and support.
- Complete an emission inventory. While this analysis yielded general information about trends and characteristics, it was beyond the scope to make an accounting of each pollutant's source. This is necessary to further focus air quality management strategy
- Complete a dispersion analysis. This is also necessary in order to properly plot the movement of pollutants into, out of and throughout the airshed. This analysis depends on whether additional high quality MET data can be found at the federally administered stations.
- Complete regular smaller studies (annual preferably) and longer term summaries similar to this study. This balances more frequent information for evaluating and adapting monitoring and management with comprehensive reflection for re-prioritizing and re-strategizing.

As we can see, the method developed by the author was able to process 12 years of continuous hourly contaminant data from a network of stations into accessible information for managers and policy makers. Managers can take guidance from table 7-1 and the summaries in the discussion for focusing efforts on priority issues, and for shaping reduction strategies and plans. Local policy makers can use the defined priority issues for developing or refining by-laws. Conversely, managers can divert resources from low priority pollutants while policies can be in the least reviewed for modification.

The method developed by the author can be generalized beyond the Sea-to-Sky Airshed. It can be used to guide the analysis of similar backlogs of data from other airsheds with continuous air quality monitoring data. It can also structure long term airshed reviews with the same type of data. While the literature analysis identified the Sea-to-Sky Airshed as being the most out of date in the airshed, at least three had research gaps of similar length to this study.

So, *how can we prevent the Sea-to-Sky Airshed's research gap from occurring again?* Adapting the findings from this thesis into the next Sea-to-Sky Airshed Ambient Air Quality summary report serves as a short-term measure. This has been contracted to occur by fall 2015. As a longer term response (and as suggested as a management recommendation), using R for analyzing airshed data will reduce future efforts to a fraction of the time thus reducing a significant barrier to airshed reporting. Offering code templates makes using R an even more attractive process to adopt. In fact, during the process of completing this thesis, the author developed such templates, and these are available upon request. Ministry employees or volunteers at the Sea-to-Sky airshed would only need to change titles and run the code to complete all the necessary graphs and operations. Should this change be adopted, the sizable resources savings will be a step forward towards bridging the airshed's gap between its data warehouse and its management system.

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## Appendix

### Plate A: R Code Templates used for Ambient Air Quality Analysis

To understand the following 'R' code templates used in the analysis please consider the following:

Comments are denoted with '#'. This is a standard symbol with which to begin any comment since this symbol communicates to the 'R' console to not run the rest of the code on that line. The customizable parts of the template are denoted with grey font. New lines of code begin with '>'. When running the code all punctuation and capitalization must remain untouched else the code will not run.

#### Preliminary 'R' Analysis

The preliminary code for all code files starts with the following:

```
> #For importing and preparing data for R
> data=read.csv(file.choose(), header=T, na.strings="-999")
> #Setting chart defaults
>      par(bty="o",          col="grey",          col.lab="gray1",
col.axis="gray1",          col.main="gray1",          fg="grey34",
cex.lab=0.95, cex.axis=0.90, cex.main=1.1, mgp=c(2,0.5,0),
mar=c(4,3.1,3.1,2.1))
```

This imports data into 'R' and sets the charting parameters such as colour and size.

Boxplots are the product from the following line of code:

```
> plot=boxplot(pollutant.1, pollutant.2, pollutant.3, etc,
ylab="title",          las=2,          main="title",
names=c("pollutant.1.name",          "pollutant.2.name",
"pollutant.3.name", etc),          pch=".",          bg="grey",
col="insert.colour",          outliers="NULL",          na.omit="-999",
outline=FALSE)
```

Histograms were calculating using:

```
> plot=hist(pollutant, breaks=100, main="insert.title",
xlab="insert.title", col="insert.colour")
```

The STL operation requires the following code:

```
>          pollutant.na.ts=ts(pollutant.na,
start=c(starting.year.of.available.data), frequency=8760)
> pollutant.na.stl=stl(pollutant.na.ts, s.window="periodic")
> plot(pollutant.na.stl, col="insert.colour")
```

The ACF function used the following base code:

```
> pollutant.na.acf=acf(pollutant.na.ts, lag.max=8760,
col="insert.colour", xlab="Time Lag (Hours)", main="title")
> pollutant.na.acf=acf(pollutant.na.ts, lag.max=168,
col="insert.colour", xlab="Time Lag (Hours)", main="title")
```

The remainder of the statistical operations require R's OpenAir package.

```
> #load openair package
> library(openair)

> #load and prepare station dataframe for openair
> insert.station.namedata=import(file = file.choose(),
file.type = "csv", sep = ",", header.at = 1, data.at = 2,
date = "Date", date.format = "%Y-%m-%d", time = "Time",
time.format = "%H:%M", tzzone = "GMT", na.strings = c("", "-999"),
ws = "WSPD_SCLR", wd = "WDIR_VECT", correct.time = NULL, strip.white=TRUE)
```

The first two lines of code loads Openair into 'R' while the remaining code loads pollutant and MET data into 'R'. This code, code for all subsequent operations was developed based off of the Openair Manual.

Base summary plot code is:

```
> summaryPlot(station.name.poll.data, clip=TRUE,
percentile=0.99, main="title", col.trend=c("darkgray"),
col.data="lavender", col.hist="grey13")
```

However, after running this code on first station it was found that there were too many monitors per station to clearly portray all labels and charts. Two new Excel files needed to thus be created for each station, one containing the MET data and the other containing the pollution data. These files were converted to csv. To then import them into 'R' the following code is required:

```
> station.name.poll.data=import(file = file.choose(),
file.type = "csv", sep = ",", header.at = 1, data.at = 2,
date = "Date", date.format = "%Y-%m-%d", time = "Time",
time.format = "%H:%M", tzzone = "GMT", na.strings = c("", "-999"),
correct.time = NULL, strip.white=TRUE)
> station.name.met.data=import(file = file.choose(),
file.type = "csv", sep = ",", header.at = 1, data.at = 2,
date = "Date", date.format = "%Y-%m-%d", time = "Time",
time.format = "%H:%M", tzzone = "GMT", na.strings = c("", "-999"),
ws = "WSPD_SCLR", wd = "WDIR_VECT", correct.time = NULL, strip.white=TRUE)
```

Running the summaryPlot() using these new dataframes yielded legible plots.

The next function, `trendLevel()`, visually represents the hourly concentration of pollution for an average day of each month of data for every year between 2002 and 2012. In one image, one can quickly determine when pollution peaks and lows occur, and can begin determining the existence of pollution patterns. The code is:

```
> trendLevel(station.namedata, pollutant="pollutant.name",
stat.args=list(na.rm=TRUE), main="title")
```

The code used for wind roses is:

```
> windRose(station.namedata, type=c("year"), paddle=FALSE,
angle=22.5, main="title")
```

Since the previous ambient air quality summary report for the Sea-to-Sky Airshed also contains wind roses, care was taken that the new wind roses be visually consistent with those of the past report. The most visually similar wind rose can be made using the false paddle style with 22.5 degree petals. Since there are several types of MET parameters, Graham Veale was consulted about which to use. Vector wind direction and scalar wind speed parameters were used to make the wind roses. Three types of wind roses were made: annual roses, seasonal roses and roses for day time and night time wind patterns. These charts can be made by replacing 'year' in the code 'type=c("year")' with 'season' or 'daylight'. Charts were made for the stations with the scalar and vector measurements: Horseshoe Bay, Langdale, Port Mellon and Squamish stations. The outcomes were then compared to the past report. It was observed that the Squamish wind roses did not resemble that in the past report. Upon closer study it appears that the newer data yields roses with similar shaped petals, although the petals have been shifted about 45 degrees north.

Basic plots for humidity and temperature were also created using the code:

```
> smoothTrend(station.namedata, pollutant="HUMIDITY",
pch=NA, main="title", ylab="title", col="dodgerblue4")
> smoothTrend(station.namedata, pollutant="TEMP_MEAN",
pch=NA, main="title", ylab="title", col="brown2")
```

By default these plots show mean monthly temperature for each year of data. Data was not chosen to be deseasonalized so that seasonal cycles are preserved to facilitate comparison with pollution data. The smooth trend function can also be customized to plot the changes in various percentiles of data over a given period of time. This function,

```
> smoothTrend(station.namedata, pollutant="pollutant.name",
statistic="percentile", percentile=c(5,50,95), main="title",
ylab="title")
```

was used to plot the 5<sup>th</sup>, 50<sup>th</sup> and 95<sup>th</sup> percentile of the data.

Openair's polar plot function visually maps at what wind direction and speed that a given pollutant comes from. This is one of the first steps in locating pollution sources. The code for this function is:

```
> polarPlot(station.namedata, pollutant="pollutant.name",
type="season", main="title")
```

This creates one seasonal and one annual polar plot by replacing ‘season’ with ‘year’ in the above code. They are a user friendly method for tracking pollution sources. Unfortunately, the only stations which contained both wind and pollutant data were the Horseshoe Bay and Langdale stations. This function could not be performed on Squamish given the inaccurate wind direction readings. Whistler, the other main community within the airshed also could not be included since the station lacks readings MET parameters. At the time of writing, alternative sources of wind data were being pursued for Whistler in order to enhance future reporting.

The last operation completed with Openair was a time variation plot. The code for these plots is the following:

```
> timeVariation(station.namedata,
pollutant="pollutant.name", c.int=c(0.99), main="title",
xlab="title", col="parameter.colour")
```

## Plate B: Similarities and Differences between Airshed Summaries and the 2004 Sea-to-Sky Ambient Air Quality Monitoring Report

### *Williams Lake Airshed*

| Similarities   | Differences  |
|--|--|
| <ul style="list-style-type: none"> <li>• Executive summary and an introduction containing a description of physical setting and history</li> <li>• The sources of pollutants (however in this case there is referencing to the emissions inventory)</li> <li>• Analysis of meteorology including wind roses and average monthly precipitation</li> <li>• Description of quality standards</li> <li>• Description of location of stations and nature of measurements</li> <li>• Using 98<sup>th</sup> percentile for analyzing 24-hr pollutant concentrations</li> <li>• Continuous and non-continuous measurement methods used</li> <li>• Pollutants analyzed with annual average concentration</li> <li>• Number of exceedances of given pollution standards</li> </ul> | <ul style="list-style-type: none"> <li>• Inclusion of PAHs and airborne metal pollutants</li> <li>• Exceedances of numerical health effect levels</li> <li>• Inclusion of percentage of time winds exceed 1m/s</li> <li>• Stronger connections drawn between the geographical conditions, MET conditions and pollution</li> <li>• Discussion of diurnal pollution trends</li> <li>• Rolling 24-hr pollutant averages</li> <li>• Explanation of air quality index results</li> <li>• Generally, there is more emphasis on textual descriptions instead of graphical illustrations, charts and discussion of aspects of numerical analysis. There is also less discussion about how the data is filtered.</li> </ul> |

### *The Lower Fraser Valley Airshed*

| Similarities  | Differences  |
|---|--|
| <ul style="list-style-type: none"> <li>• Summary is comparable to executive summary of Sea-to-Sky report</li> </ul> | <ul style="list-style-type: none"> <li>• Inclusion of ammonia, VOC and black carbon pollutants and visual air quality index and</li> </ul> |

|  |  |
|--|--|
| <ul style="list-style-type: none"> <li>• Introduction with purpose, description of air quality monitoring network and stations, description of pollutants monitored, air quality objectives and standards</li> <li>• Pollutants reported as annual averages and compared to Federal and provincial standards</li> <li>• Pollutant sources discussed</li> <li>• Summary of regional long term trends</li> <li>• Maps of location of monitoring stations per each pollutant throughout the airshed</li> <li>• Wind roses for each station shown on map of airshed</li> </ul> | <p>reporting</p> <ul style="list-style-type: none"> <li>• Description of AQHI and analysis results</li> <li>• Specialized air quality monitoring methods</li> <li>• Number and summary of air quality advisories</li> <li>• Graph of total precipitation per city</li> <li>• Hourly maximum and minimum average air temperatures, with graphical illustration</li> <li>• Graph of daily precipitation over the year (presented as a range of measurements from all stations)</li> <li>• Description of network operations (partners, quality assurance and control, database)</li> <li>• Pollutant data is analyzed differently: instead of straight 1-hr and 24-hour averages, this report uses rolling averages. Maps of short-term pollutant peaks (1-hr) are shown on an airshed map. Frequency distributions are also given for exceedances of objectives and standards.</li> <li>• 99<sup>th</sup> percentile is used for analyzing 1-hr concentrations whereas the Sea-to-Sky report uses 25<sup>th</sup> and 75<sup>th</sup> for ozone and 98<sup>th</sup> for several other pollutants.</li> <li>• Diurnal data represented as line graphs of average daily values as opposed to data maps with each hourly measurement shown as an average coloured stripe over the year</li> <li>• Annual average pollutant concentrations are also graphed by station</li> </ul> |
|--|--|

*Parkland Airshed Management Zone*

| Similarities   | Differences   |
|--|---|
| <ul style="list-style-type: none"> <li>• Map of airshed and monitoring stations</li> <li>• Description of monitoring system, methods and management</li> <li>• Summary of pollutant characteristics and sources, annual averages</li> <li>• Long term average annual pollutant trends</li> </ul> | <ul style="list-style-type: none"> <li>• Inclusion of total hydrocarbons, lack of inclusion of all MET data except temperature</li> <li>• Outline of the monitoring organization’s mission, vision and goals</li> <li>• Management plans for specific pollutants</li> <li>• Summary of community outreach efforts (including a satisfaction survey)</li> <li>• A section explaining how the public can become involved</li> <li>• Comparison of pollutant levels to other locations within province and within airshed</li> <li>• Isopleth diagram for annual average ozone</li> </ul> <p>*organization specific sections such as board of directors are not differences as they are not relevant to the Sea-to-Sky government management scheme.</p> |

*Air Quality in Saskatchewan*

Saskatchewan is an interior province of Canada and conducted an air quality review for province wide air pollution between 2000 and 2009.

| Similarities  | Differences  |
|---|--|
| <ul style="list-style-type: none"> <li>• Executive summary and introduction</li> <li>• Chart of types of data and types of pollutants monitored at stations</li> <li>• History of air quality monitoring</li> <li>• Annual pollutant 1-hr and 24-hr maximums, and annual average maximum per station</li> <li>• Use of continuous and non-continuous data</li> <li>• Discussion of pollutant characteristics, general human and environmental health effects</li> </ul> | <ul style="list-style-type: none"> <li>• No TRS or analysis of meteorology, the province did not have stations capable of MET measurements at the time</li> <li>• Discussion and analysis of AQI readings (please note that the calculations behind this indicator have since been changed and the indicator has been renamed to AQHI)</li> <li>• Date of maximum pollutant reading</li> <li>• Summary section of main pollution trends, that being said this was a very short and generalized section</li> <li>• 8-hr instead of 24-hour maximum used for CO, PM and O<sub>3</sub></li> <li>• Line graph used instead of data map for daily pollution levels</li> </ul> |

*Air Quality Standards Compliance Report for South Coast Basin, California*

| Similarities  | Differences  |
|---|--|
| <ul style="list-style-type: none"> <li>• Listing ambient air quality standards</li> </ul> | <ul style="list-style-type: none"> <li>• Inclusion of lead and sulphates</li> <li>• Pollutant levels shown as a percentage of standards (with each pollutant's temporal measurement corresponding to the time period associated with the standard, e.g. 1-hr or 8-hr averages)</li> <li>• Graph of annual total number of ozone standard exceedances over six years</li> <li>• Total hours of ozone standard exceedances for fourteen years</li> <li>• Map of total hours of exceedances for each pollutant around air basin in 2005, using annual arithmetic mean</li> <li>• Maximum levels of pollutants listed without averaging</li> <li>• Comparison of air quality results to different areas</li> </ul> |

*Trends in Bay Area Ambient Particulates*

| Similarities   | Differences  |
|--|--|
| <ul style="list-style-type: none"> <li>• Summary (similar to executive summary although includes much more detailed overview of report results) and introduction</li> <li>• Chart of station pollutants measured and dates of operation</li> </ul> | <ul style="list-style-type: none"> <li>• Detailed methods for measuring PM, and for combining data into trends</li> <li>• Annual trends contain confidence intervals, and are sometimes calculated using geometric mean</li> </ul> |

|  |   |
|--|---|
| <ul style="list-style-type: none"> <li>• Discussion of health problems, standards</li> <li>• Summary of average annual PM levels in comparison to standards, although some charts compare multiple years based on quarterly averages</li> <li>• 98<sup>th</sup> PM percentiles used, but the application does differ in that it is used for three year rolling averages</li> </ul> | <ul style="list-style-type: none"> <li>• Composition of PM, changes in composition, trends of PM components</li> <li>• Trends in number of annual and seasonal exceedances of the standards</li> <li>• Trends in annual PM design values</li> <li>• Comparison of the results for two neighbouring basins</li> <li>• Comparison to trends in emissions inventory</li> <li>• Mean annual reductions in PM</li> <li>• Section on statistical methods used for conducting analysis</li> <li>• Estimated health impacts of changes (instead of a general discussion of health effects)</li> <li>• Evaluating exceedance potential by calculating correlation between conditions and PM levels, average exceedance potential</li> <li>• Uncertainty given for 24-hr estimates</li> <li>• Graph of annual geometric mean for chloride, potassium and carbon 14(used since Chloride is a marker of sea air, potassium can be used to mark wood burning, and carbon 14 can indicate activities such as fossil fuel combustion or wood burning)</li> </ul> |
|--|---|

*New York City Trends in Air Pollution and its Health Consequences*

| Similarities   | Differences  |
|--|--|
| <ul style="list-style-type: none"> <li>• Executive summary and introduction</li> </ul> | <ul style="list-style-type: none"> <li>• History of management efforts instead of history of Sea-to-Sky's monitoring efforts</li> <li>• Reporting initiatives, programs and their progress to date in reducing pollution</li> <li>• Goals</li> <li>• Explanation of survey methods</li> <li>• Map and discussion of annual reductions in winter only</li> <li>• Line graph of three year trends in annual pollutants compared to levels in other cities</li> <li>• Impact of policies on air quality and progress towards goals</li> <li>• Estimated health benefits arising from changes</li> <li>• Remaining challenges</li> </ul> |

*EU Air Quality Report*

| Similarities  | Differences   |
|---|---|
| <ul style="list-style-type: none"> <li>• Executive summary, background</li> <li>• Characteristics and sources of pollutants</li> <li>• Air pollution and general effects on human health and the environment</li> <li>• Pollutants shown as average annual long term</li> </ul> | <ul style="list-style-type: none"> <li>• Ammonia, methane and VOC emissions included, some discussion of airborne metals and benzene</li> <li>• Objectives and coverage</li> <li>• Sources and emissions of ozone precursors</li> </ul> |

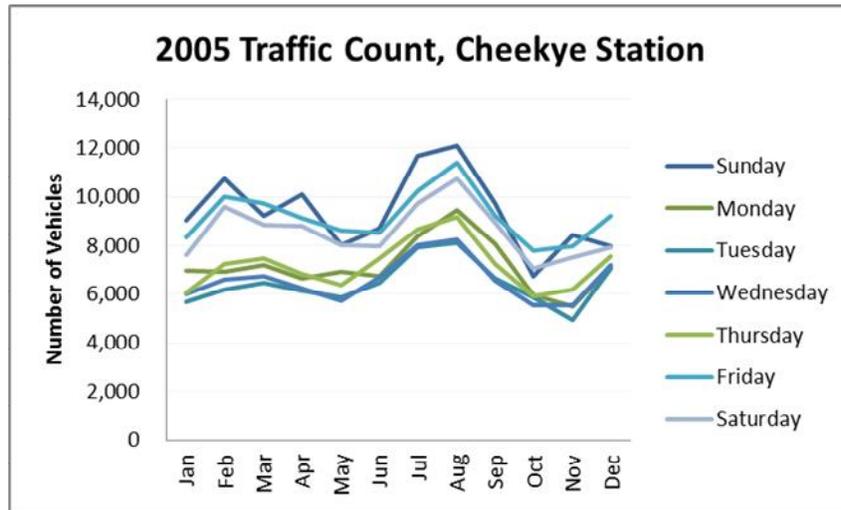
|  |  |
|--|--|
| <p>trends and data coverage, however confidence limits, total number of monitoring stations and total stations showing significant trends and standard deviation are added</p> <ul style="list-style-type: none"> <li>• Discussion of location and times of exceedances</li> </ul> | <ul style="list-style-type: none"> <li>• Policy response instruments and legislation, strategy, legal instruments, policy analysis, policy responses on national, regional and local levels</li> <li>• Line graph of source contributions to pollutants, discussion of the relationship between emissions and ambient concentrations</li> <li>• Description of high PM pollution episodes (one map of daily mean PM levels in Europe included)</li> <li>• Changes in pollutant levels over time frame expressed as percentages</li> <li>• Countries compared using a bar graph of three year average concentrations</li> <li>• Variations in content of PM, and of differences between urban and rural trends</li> <li>• PM and ozone concentrations expressed as 90.4, and 93.2 percentile of daily average, percentage valid measurements indicated. Results are illustrated as coloured points throughout a map of Europe. NO<sub>2</sub>, metals, benzene and CO are presented similarly, except data sorting with percentiles.</li> <li>• Graph showing average attainment status for various pollutants in terms of standards for the EU-28 (error bars included)</li> <li>• Air pollution effects on climate change, chart of radiative forcing included</li> <li>• Summary of critical levels of SO<sub>2</sub>, NO<sub>x</sub>, O<sub>3</sub> for the protection of vegetation, discussion of exceedances, map of exposure impacts on agricultural areas affected. Similar map for exposure to European forested areas. Ecosystem areas were also described in terms of percent at risk of certain effects such as eutrophication, acidification and toxic metals.</li> <li>• Population exposure, and consequent impacts on health. Chart of premature deaths from PM<sub>2.5</sub> and O<sub>3</sub> exposure per EU country</li> </ul> |
|--|--|

*Malmö 2013 air study*

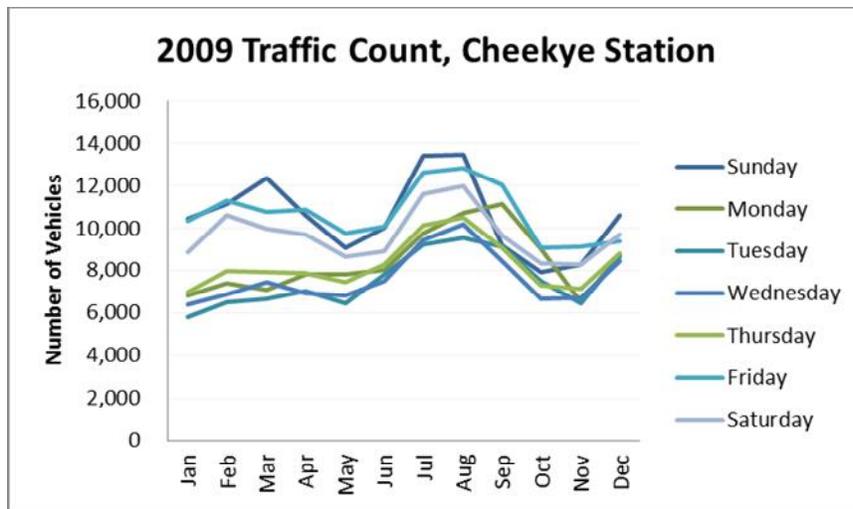
| Similarities  | Differences  |
|---|--|
| <ul style="list-style-type: none"> <li>• Introduction with map of airshed and station locations, and a chart of stations with their nature of measurements</li> <li>• Daily min, max and average temperatures</li> <li>• Annual mean concentration of pollutants, discussion of exceedances</li> <li>• Hours of data</li> <li>• General health effects and effects on natural environment</li> <li>• History of monitoring</li> </ul> | <ul style="list-style-type: none"> <li>• Heavy metals and PAH pollutants studied in almost equal detail to typically studied pollutants</li> <li>• Graph of average monthly temperature and precipitation in comparison to historical averages</li> <li>• Spider diagrams used to express wind data instead of wind roses</li> <li>• Number of hours that wind surpasses 1m/s</li> <li>• Map of one average pollutant per meter</li> </ul> |

|  |  |
|--|--|
| <ul style="list-style-type: none"> <li>• Results from mobile stations</li> <li>• Pollutant standards, photos and descriptions of stations</li> <li>• 98<sup>th</sup> percentile daily average of pollutants</li> </ul> | <p>squared throughout the city of Malmö, map of streets with risk of exceedances</p> <ul style="list-style-type: none"> <li>• Percentage contributions of emissions sources</li> <li>• Analysis of vehicles and emission: percentage of diesel cars in Sweden, emissions of NO<sub>x</sub> in grams per vehicle kilometer for key fuel types</li> <li>• Explanation of measures undertaken to improve air quality</li> <li>• Discussion of results and conclusion</li> </ul> |
|--|--|

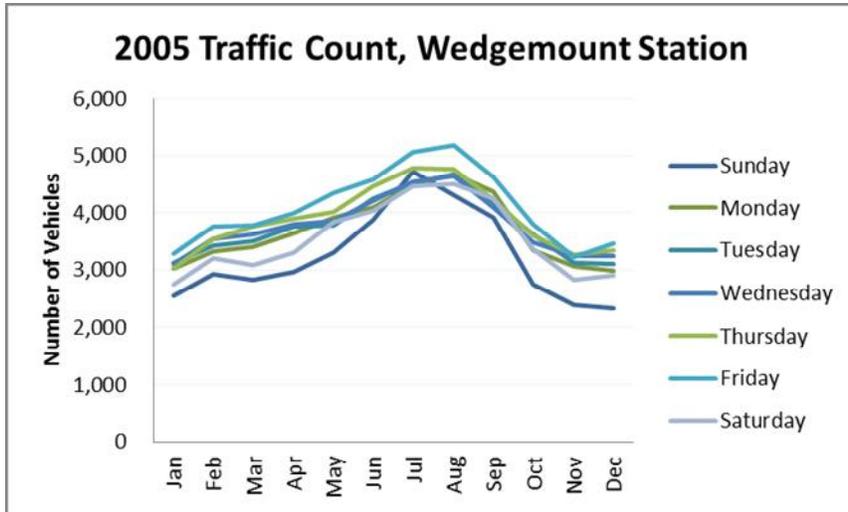
Plate C: Traffic Charts



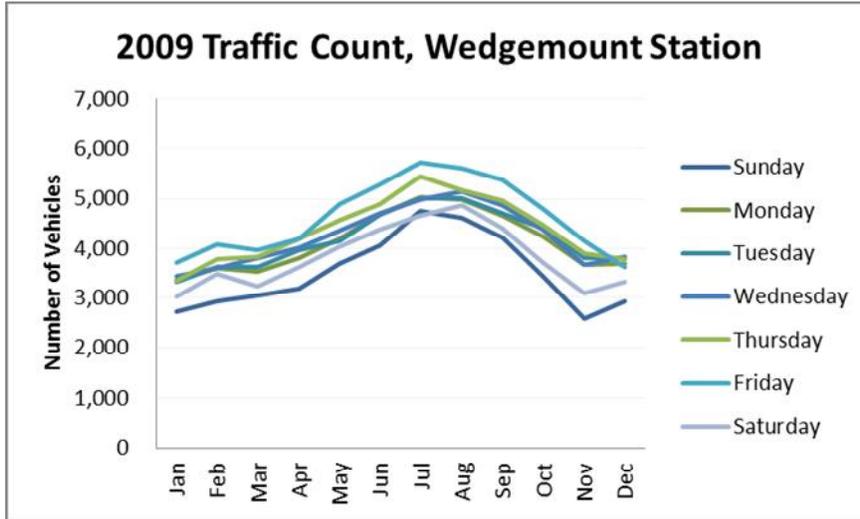
Object C-1 'Graph of monthly vehicles passing the Cheekye traffic counting station for each day in 2005'



Object C-2 'Graph of monthly vehicles passing the Cheekye traffic counting station for each day in 2009'



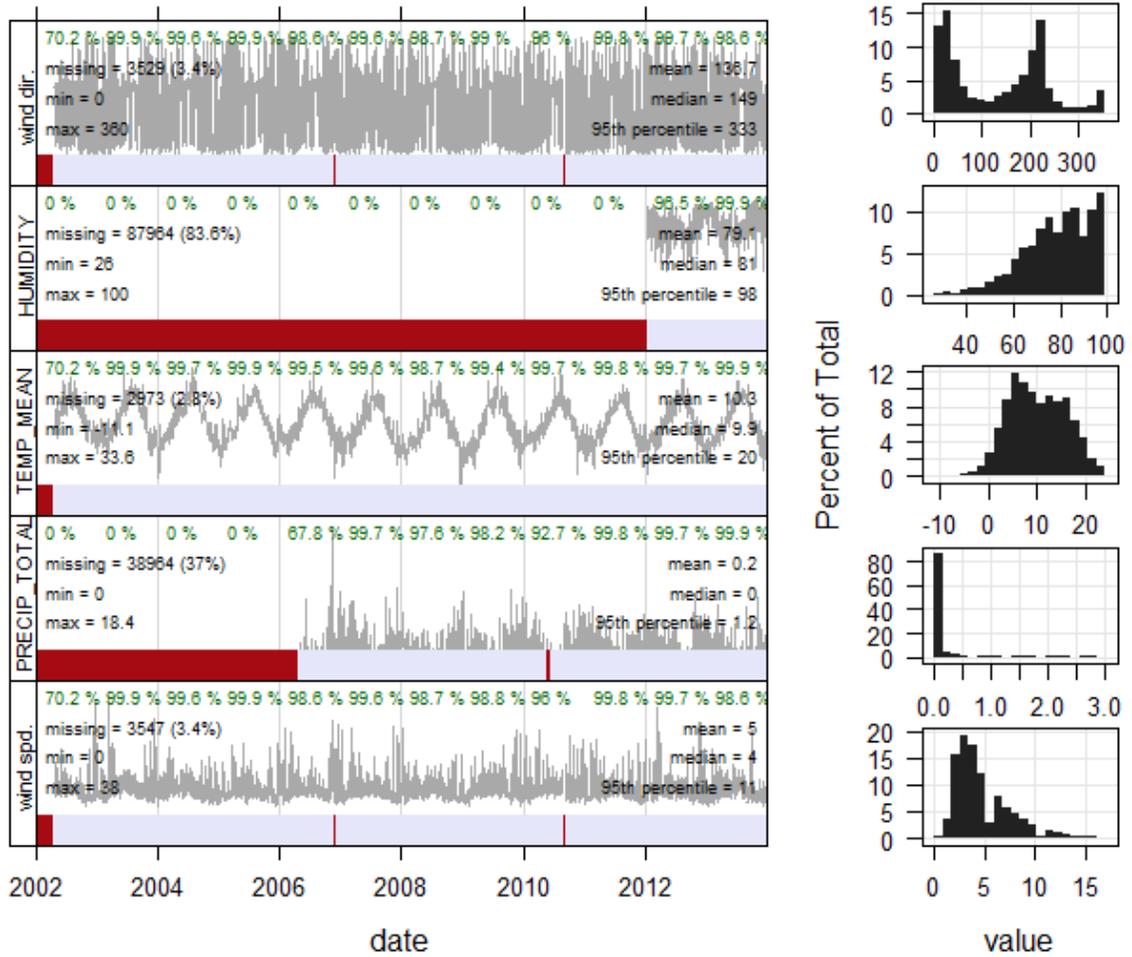
Object C-3 'Graph of monthly vehicles passing the Wedgemount traffic counting station for each day in 2005'



Object C-4 'Graph of monthly vehicles passing the Wedgemount traffic counting station for each day in 2009'

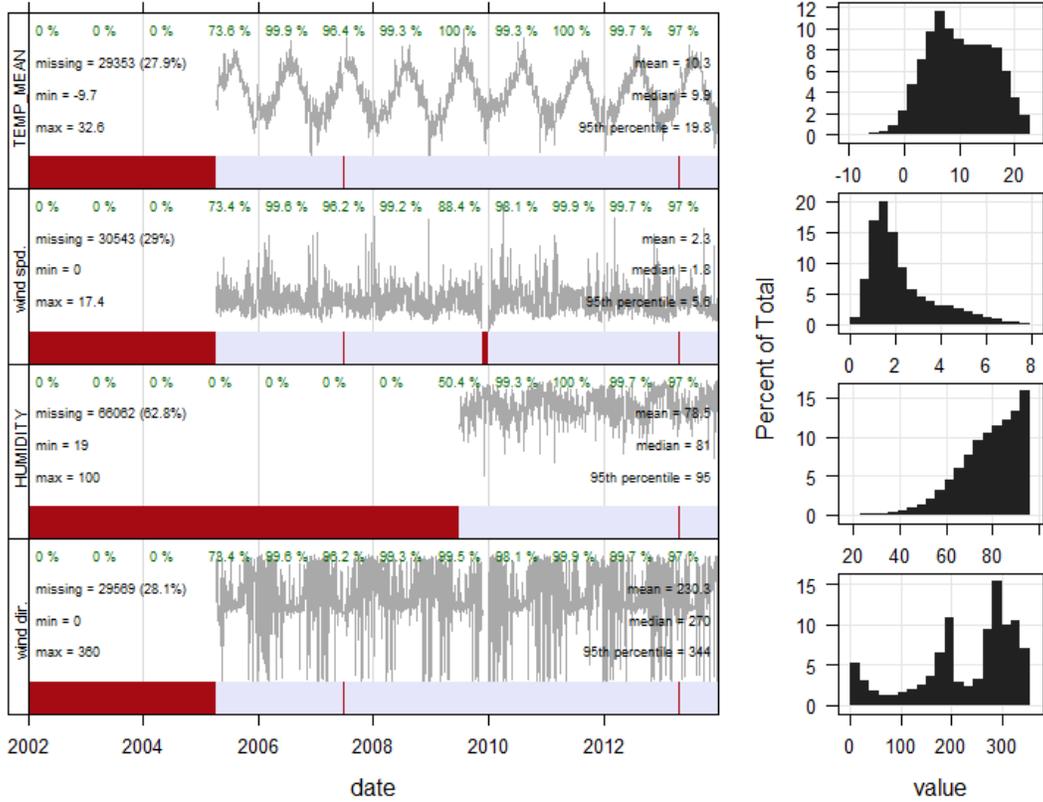
Plate D: MET Charts

### Summary Plot for Horseshoe Bay Station MET Data



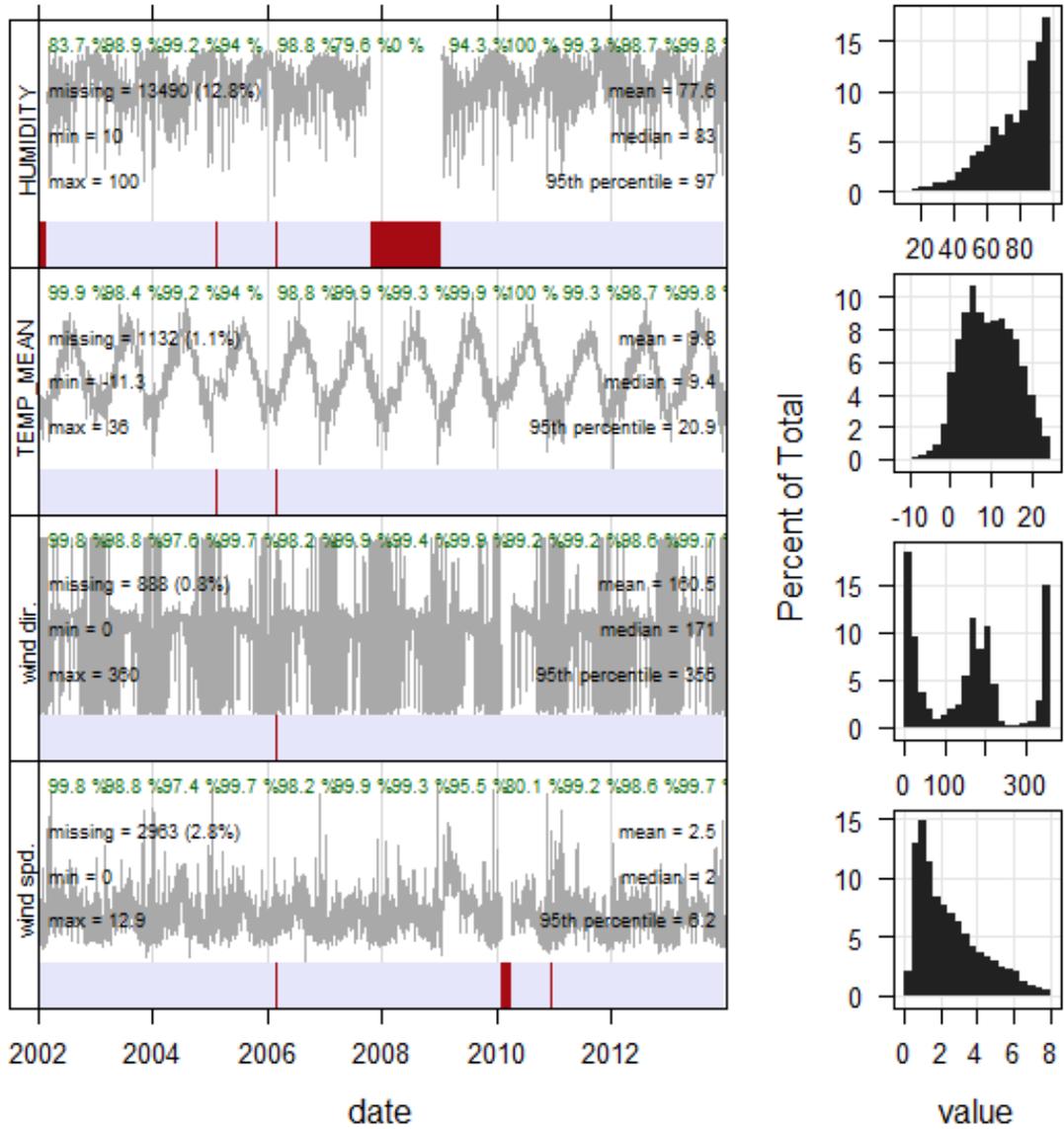
Object D-1 'Summary plot of recorded Horseshoe Bay station MET data'

### Summary Plot for Langdale Station MET Data

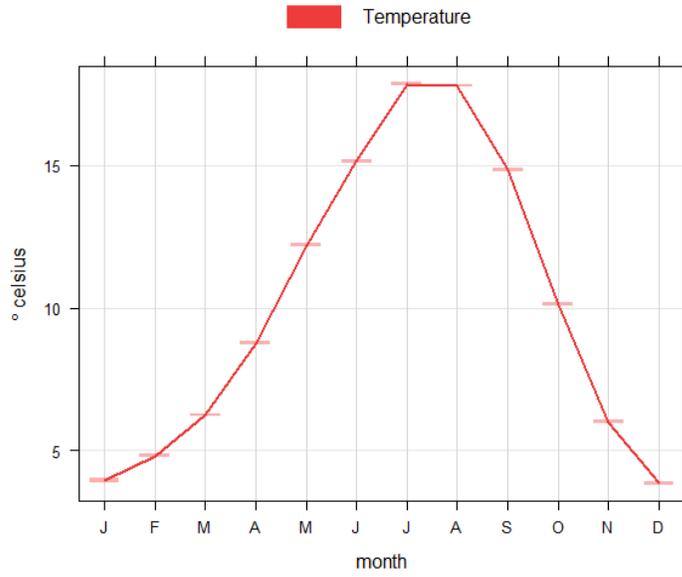


Object D-2 'Summary plot of recorded Langdale station MET data'

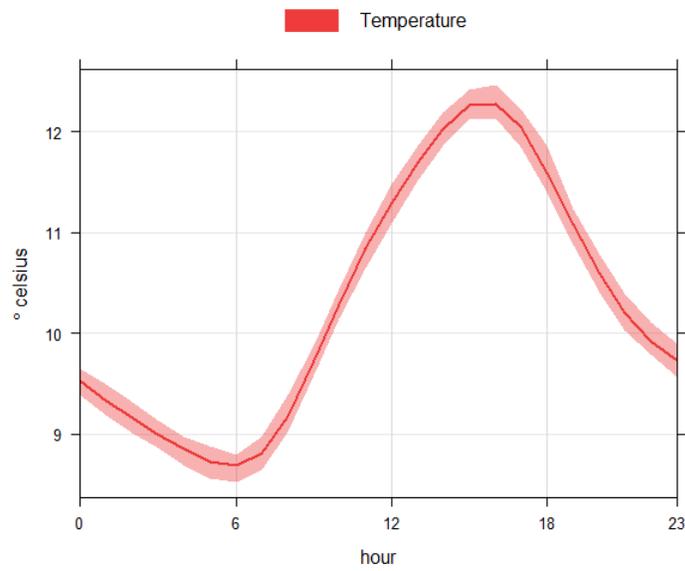
## Summary Plot for Squamish Station MET Data



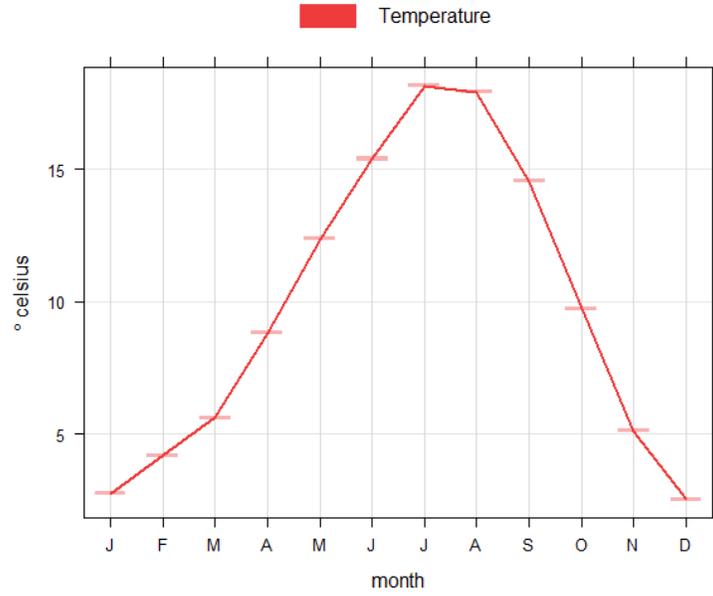
Object D-3 'Summary plot of recorded Squamish station MET data'



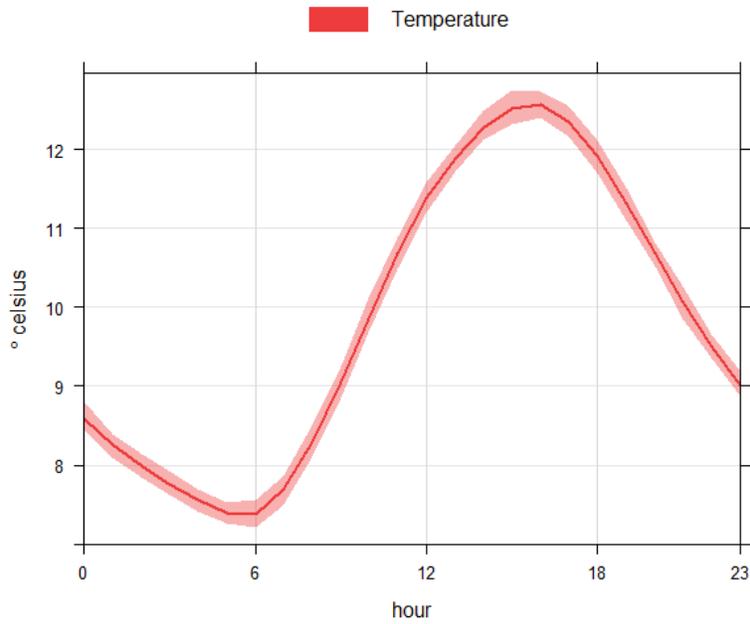
Object D-4 'Monthly plot of Horseshoe Bay average temperature readings between 2001 and 2013'



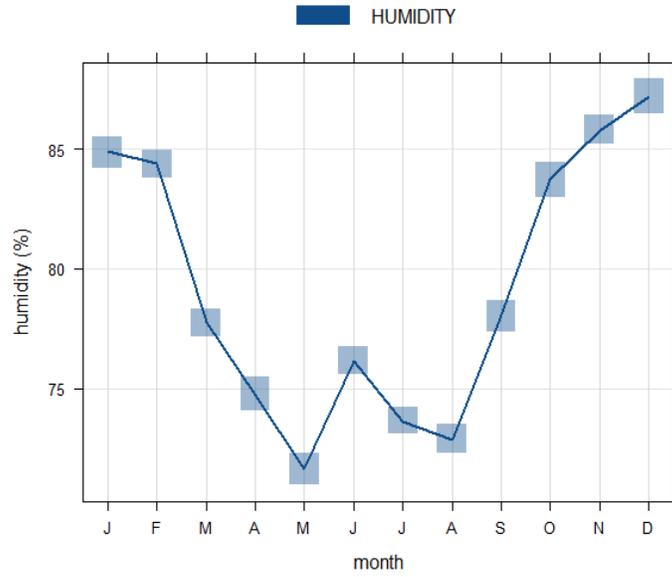
Object D-5 'Diurnal plot of Horseshoe Bay average temperature readings between 2001 and 2013'



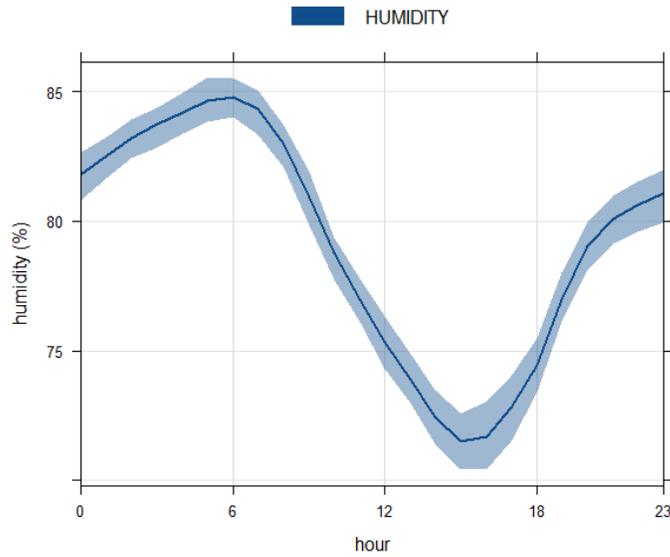
Object D-6 'Monthly plot of Squamish average temperature readings between 2001 and 2013'



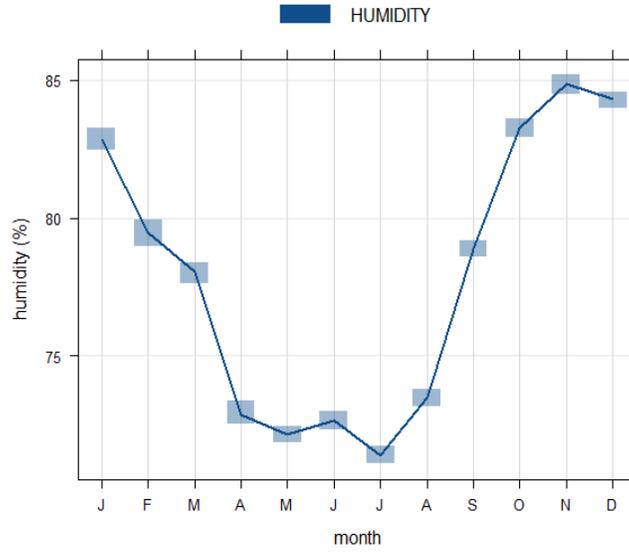
Object D-7 'Diurnal plot of Squamish average temperature readings between 2001 and 2013'



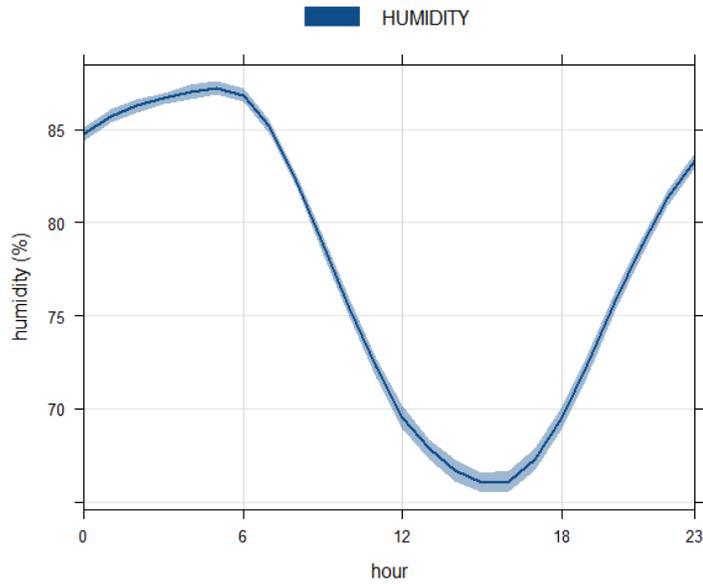
Object D-8 'Monthly plot of 2002-2013 Horseshoe Bay humidity readings'



Object D-9 'Diurnal plot of 2002-2013 Horseshoe Bay humidity readings'



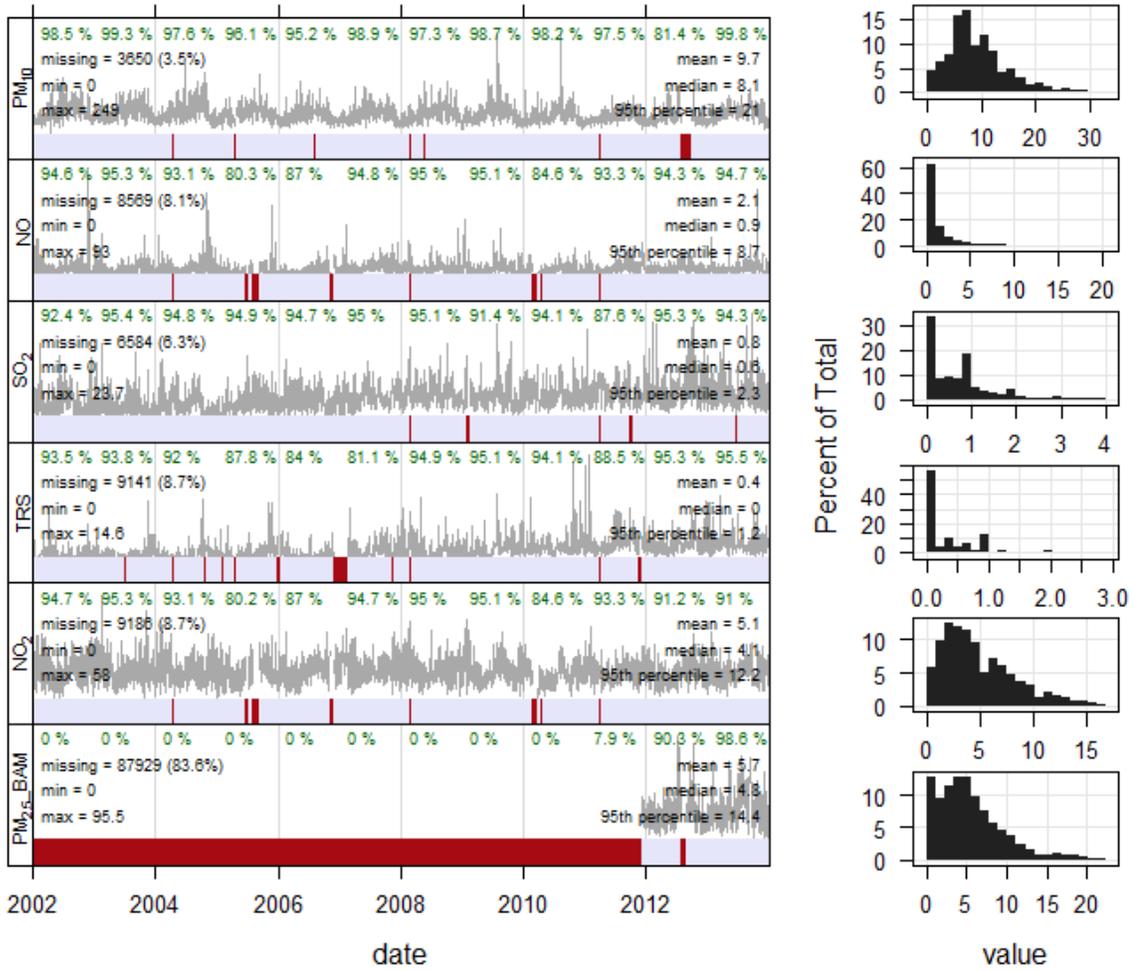
Object D-10 'Monthly plot of 2002-2013 Horseshoe Bay humidity readings'



Object D-11 'Hourly plot of 2002-2013 Horseshoe Bay humidity readings'

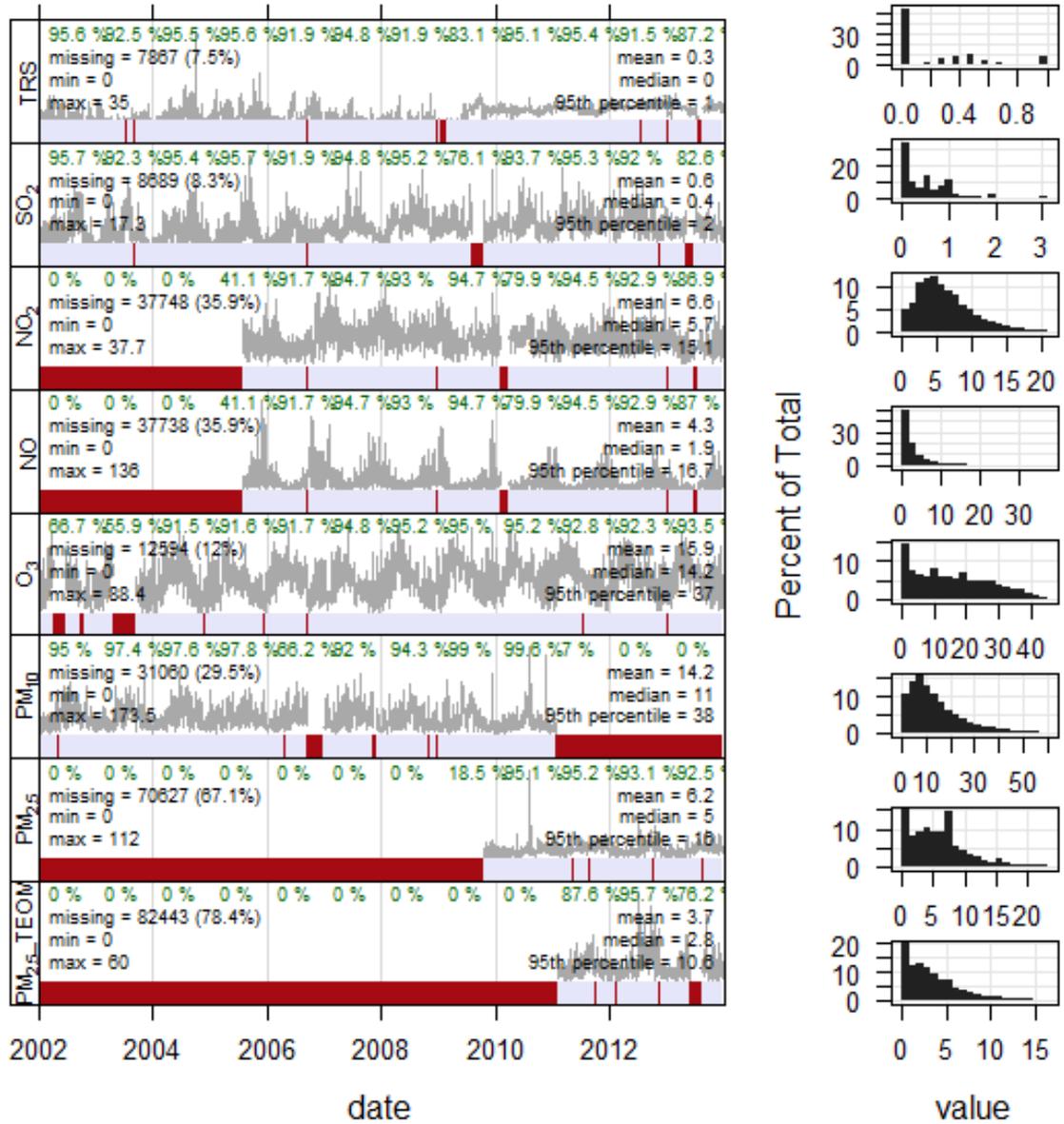
## Plate E: Air Pollutant Charts

### Summary Plot for Langdale Station Pollutant Data



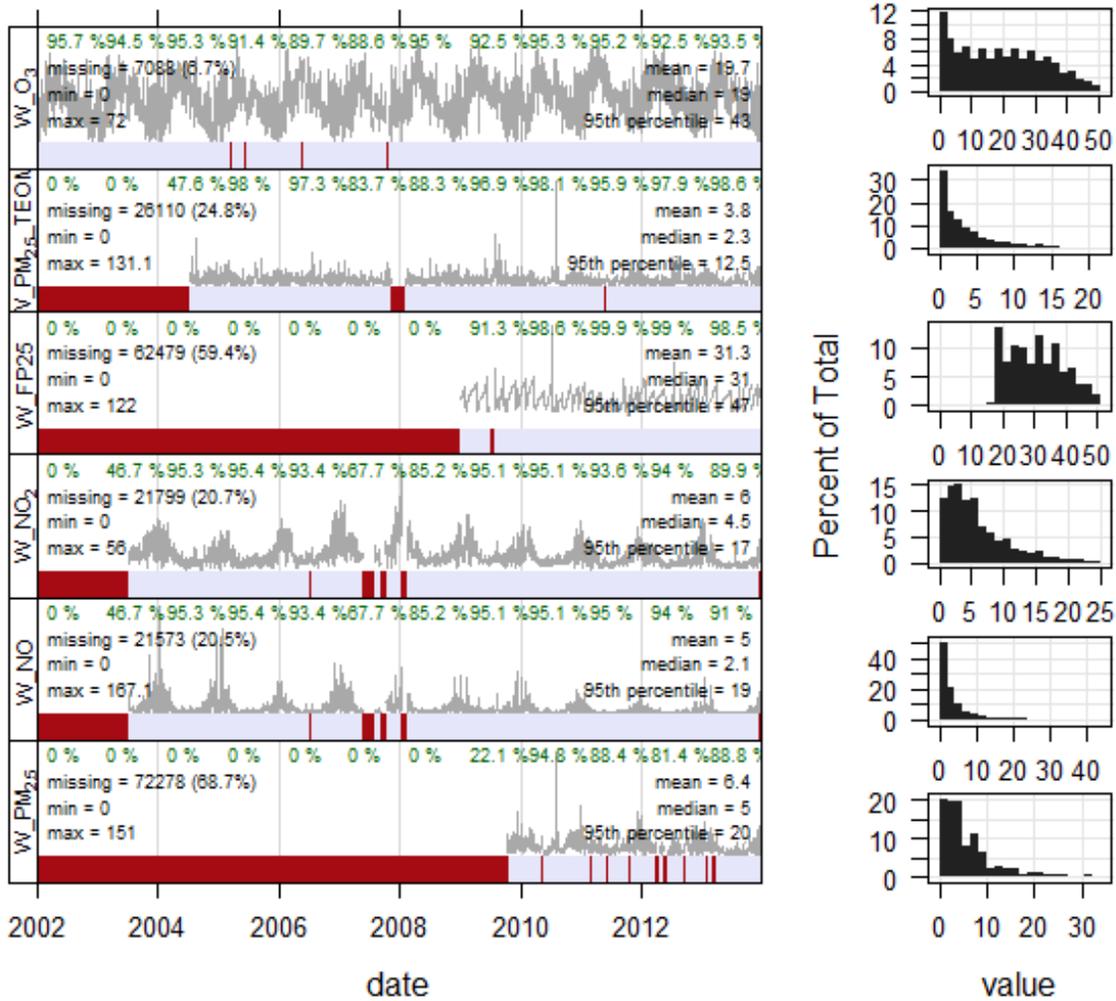
Object E-1 'Station summary plot for pollutants recorded at Langdale station between 2001 and 2013'

## Summary Plot for Squamish Station Pollutant Data

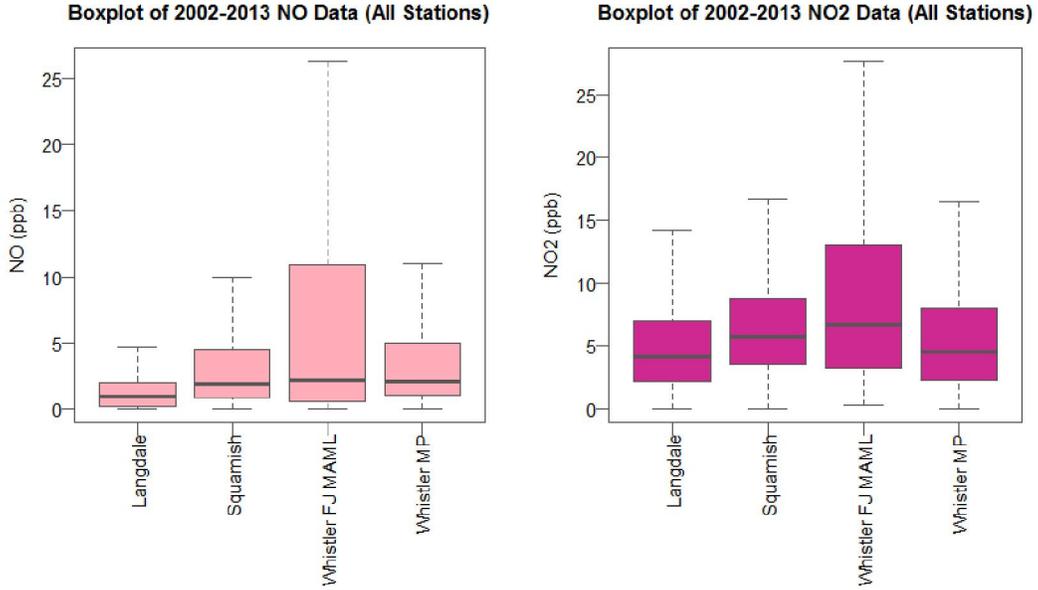


Object E-2 'Station summary plot for pollutants recorded at Squamish station between 2001 and 2013'

### Summary Plot for Whistler Station Pollutant Data

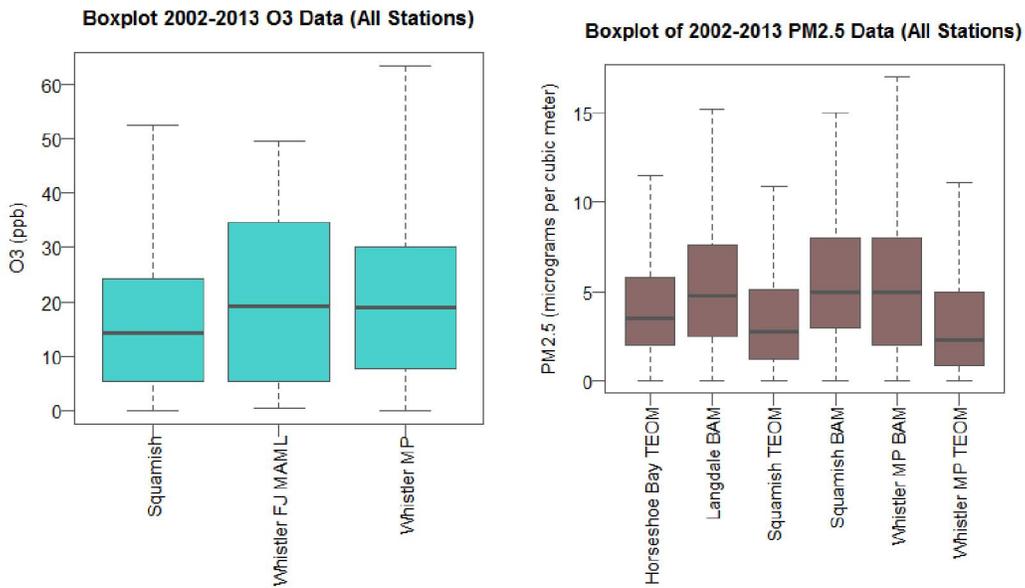


Object E-3 'Station summary plot for pollutants recorded at Whistler Meadow Park station between 2001 and 2013'



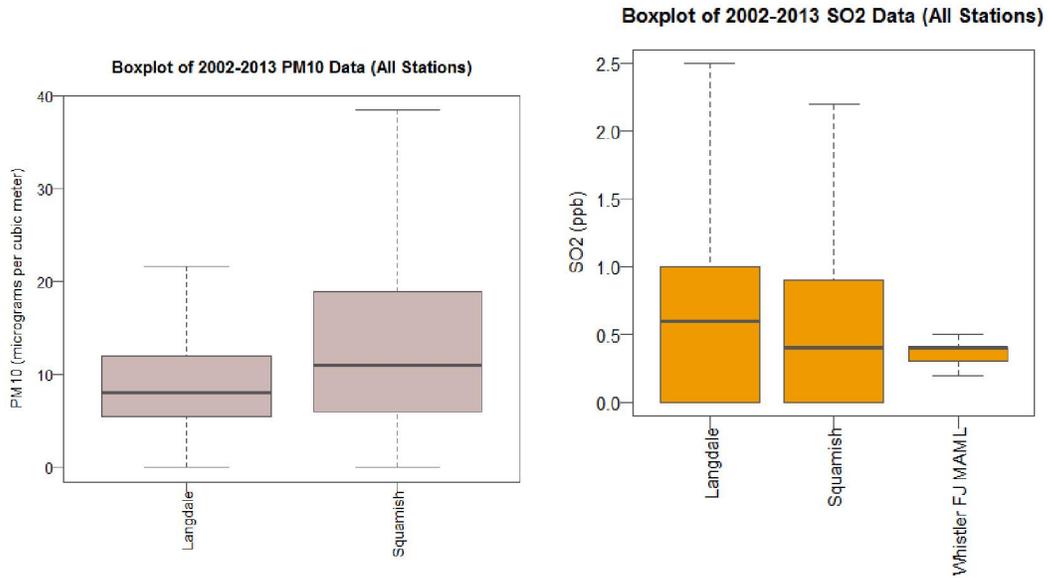
Object E-4 (left) 'Boxplots for NO data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'

Object E-5 (right) 'Boxplots for NO<sub>2</sub> data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'



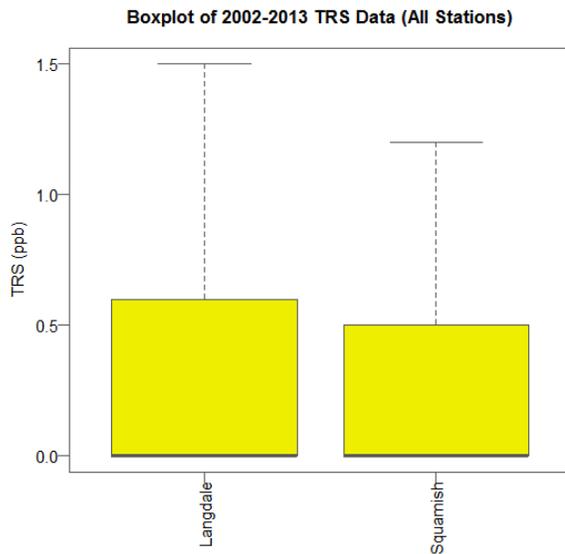
Object E-6 (left) 'Boxplots for O<sub>3</sub> data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'

Object E-7 (right) 'Boxplots for PM<sub>2.5</sub> data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'



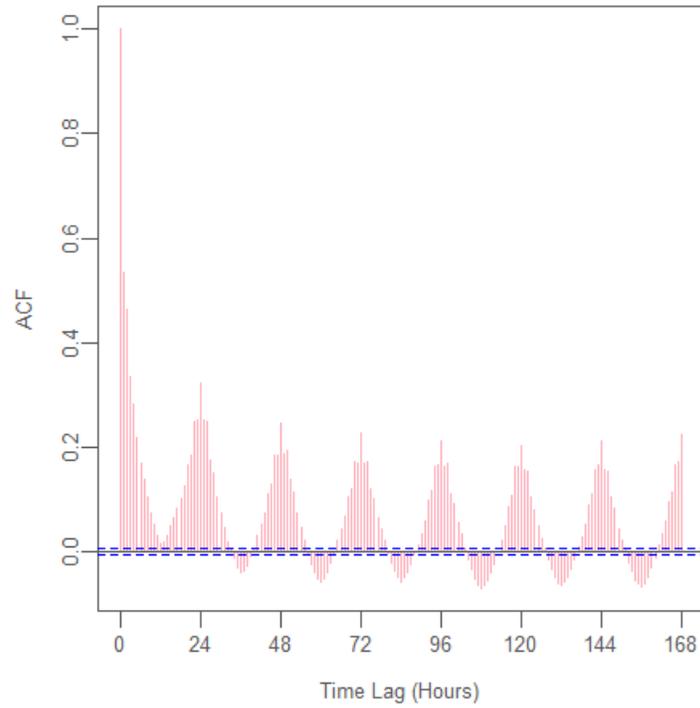
Object E-8 (left) 'Boxplots for PM<sub>10</sub> data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'

Object E-9 (right) 'Boxplots for SO<sub>2</sub> data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'



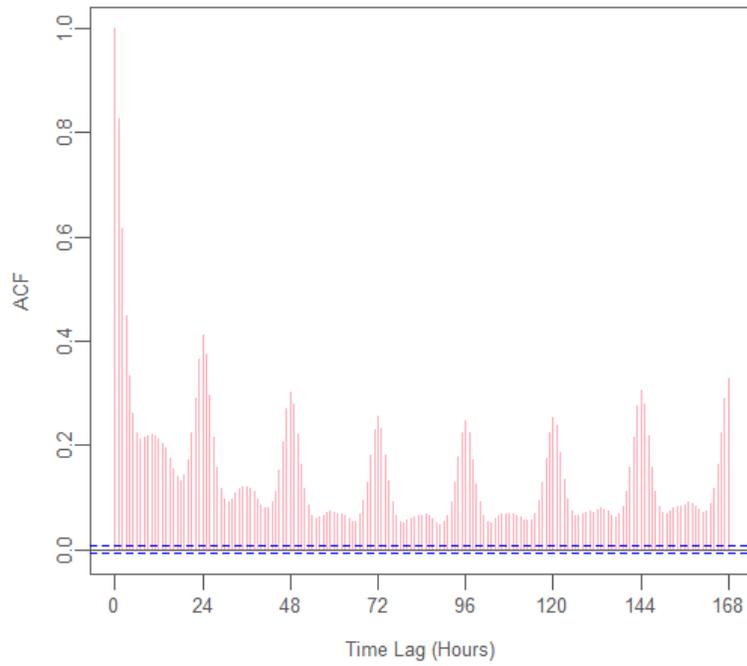
Object E-10 (left) 'Boxplots for NO data recorded between 2001 and 2013 across all stations in the Sea-to-Sky airshed'

**Autocorrelation Plot for Langdale NO Data (Week)**



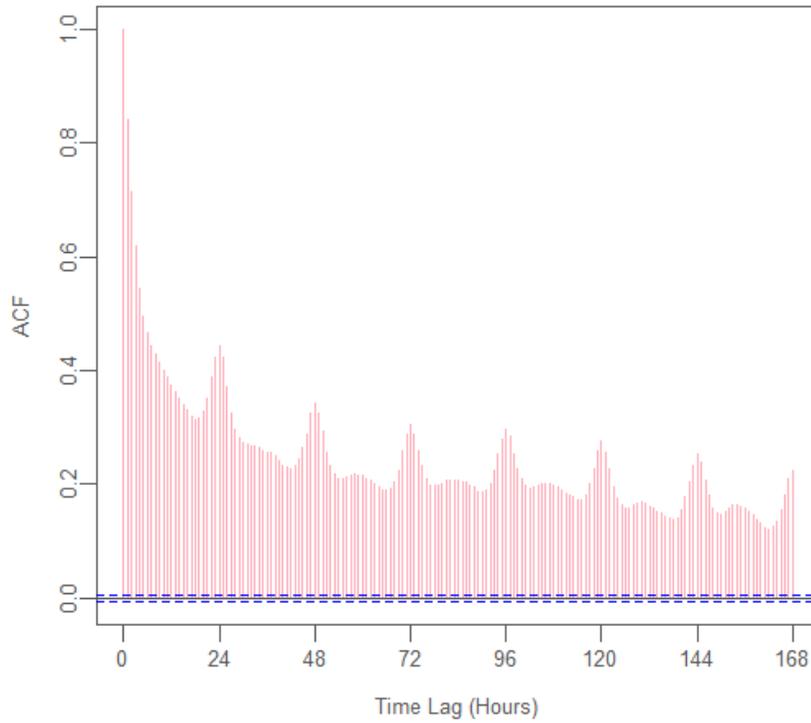
*Object E-11 'ACF graph of Langdale NO between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Squamish NO Data (Week)**



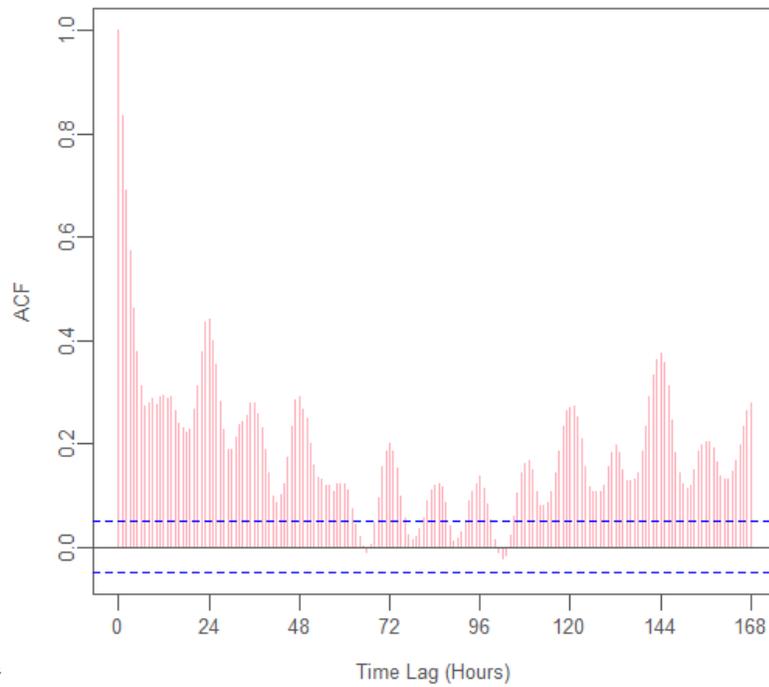
*Object E-12 'ACF graph of Squamish NO between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Whistler NO Data (Week)**



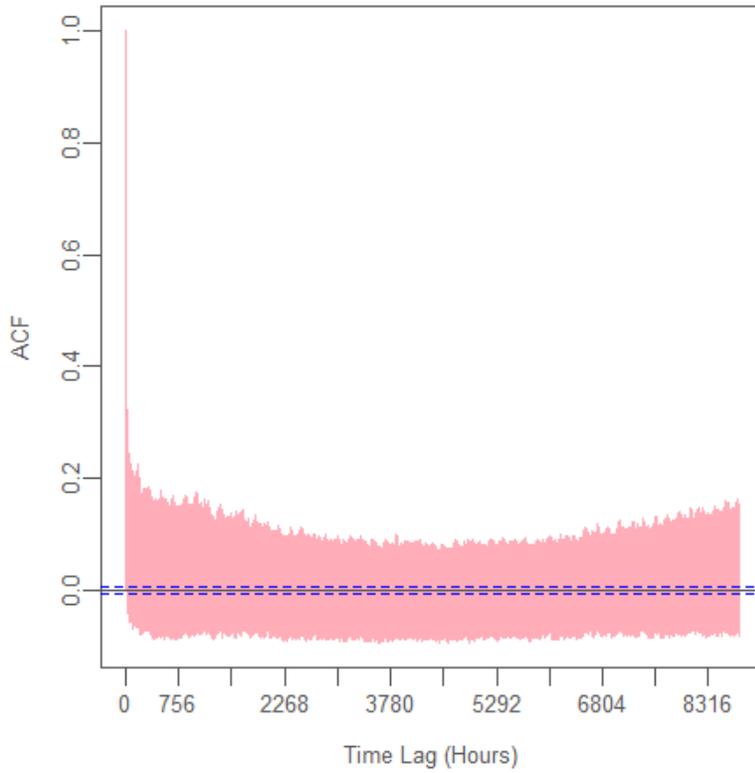
*Object E-13 'ACF graph of Whistler NO between 2001 and 2013, with time lag of up to one week*

**Autocorrelation Plot for Whistler FJ MAML NO Data (Week)**



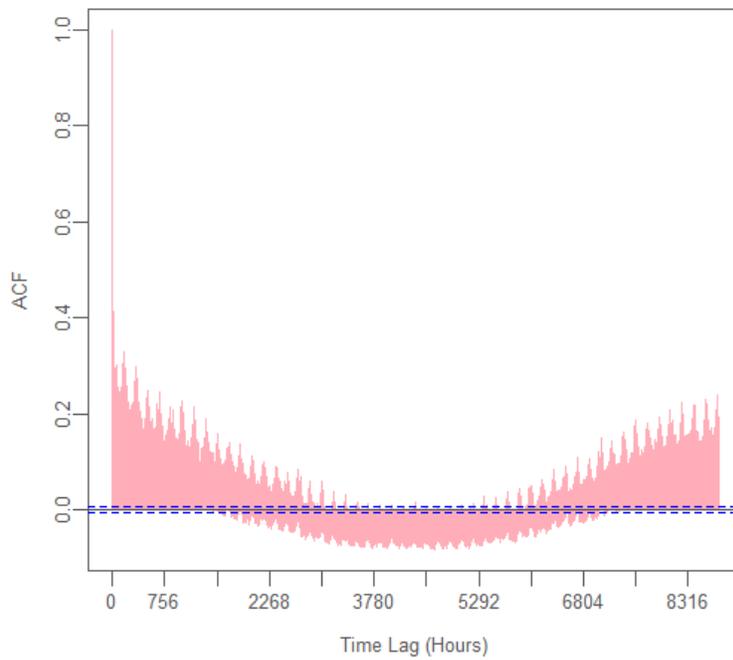
*Object E-14 'ACF graph of Whistler Function Junction NO between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Langdale NO Data (Year)**

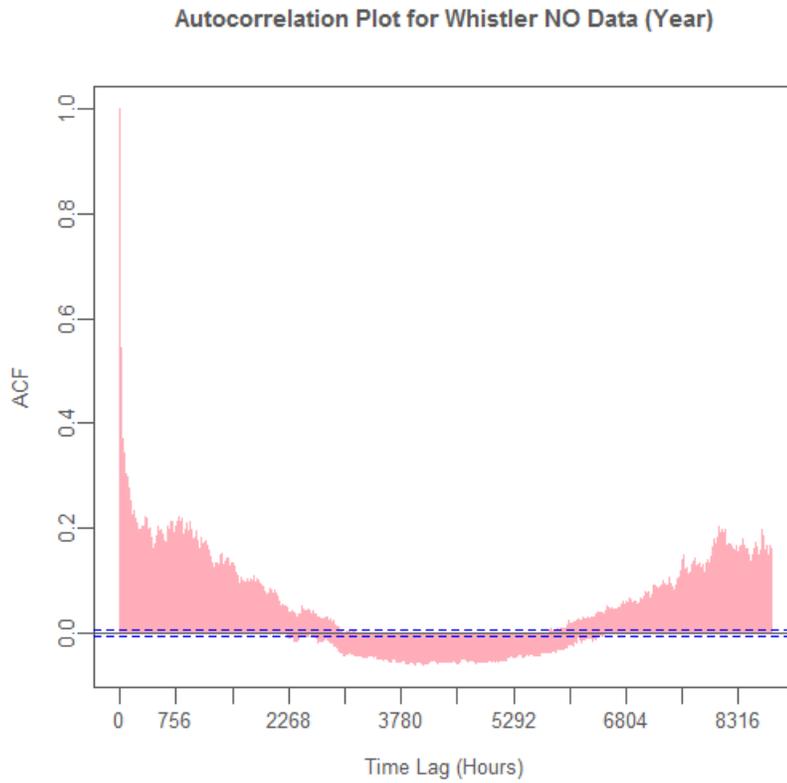


*Object E-15 'ACF graph of Langdale NO between 2001 and 2013, with time lag of up to one year'*

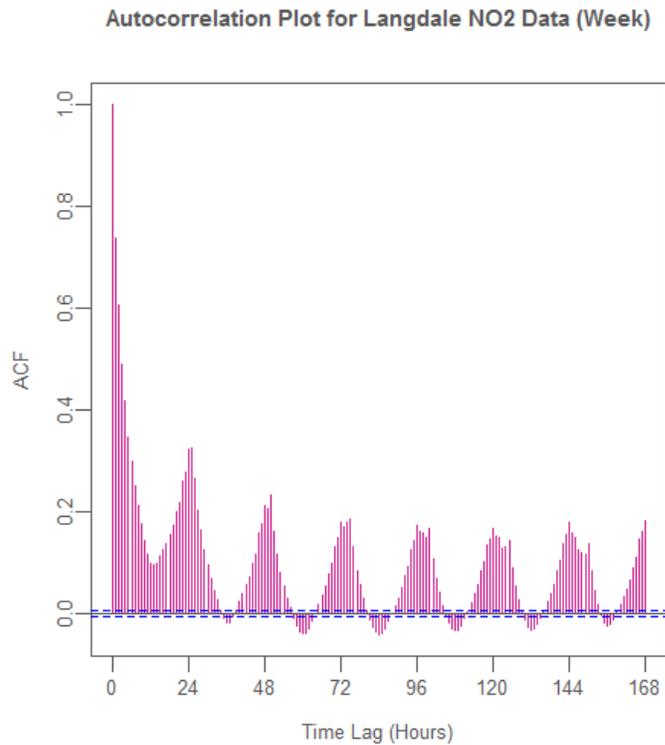
**Autocorrelation Plot for Squamish NO Data (Year)**



*Object E-16 'ACF graph of Squamish NO between 2001 and 2013, with time lag of up to one year'*

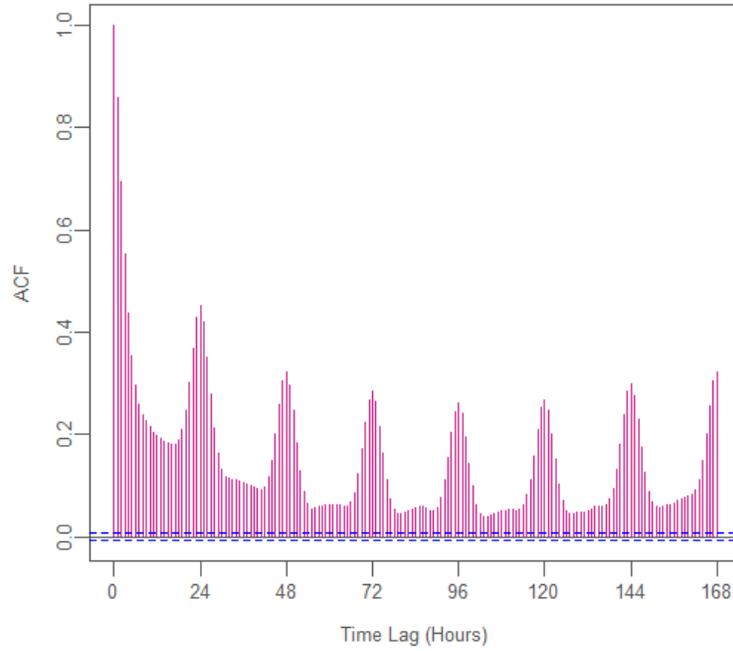


Object E-17 'ACF graph of Whistler NO between 2001 and 2013, with time lag of up to one year'



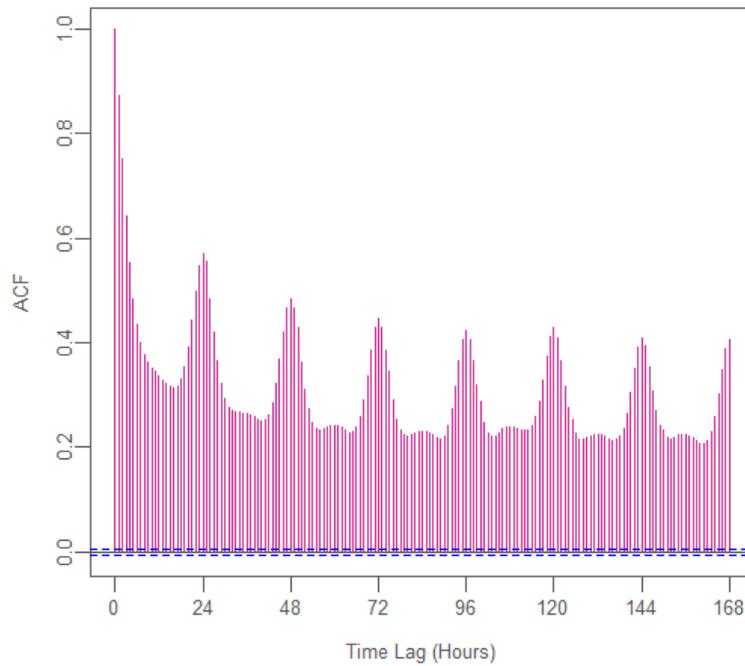
Object E-18 'ACF graph of Langdale NO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'

Autocorrelation Plot for Squamish NO<sub>2</sub> Data (Week)

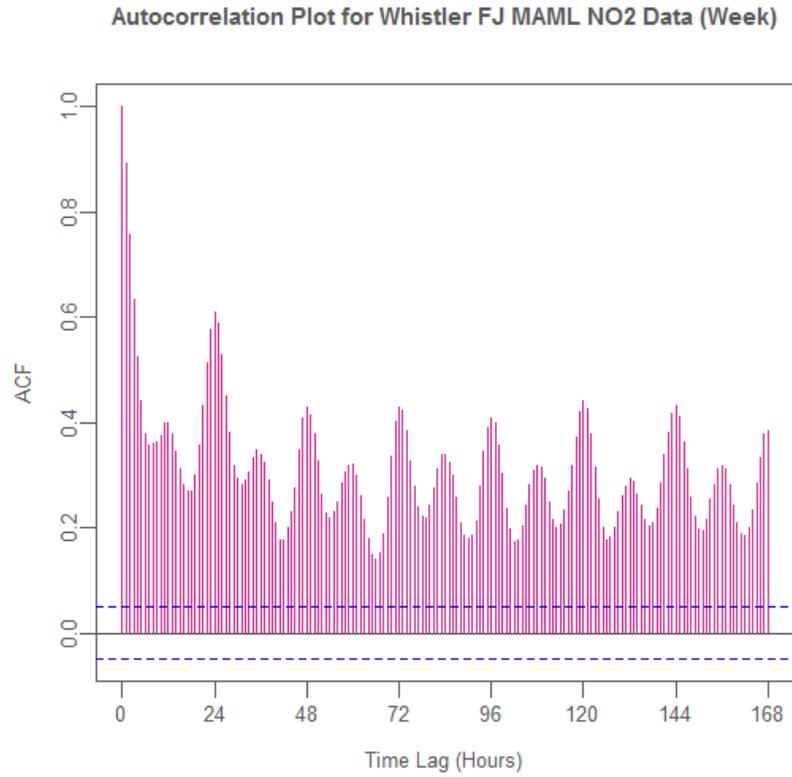


Object E-19 'ACF graph of Squamish NO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'

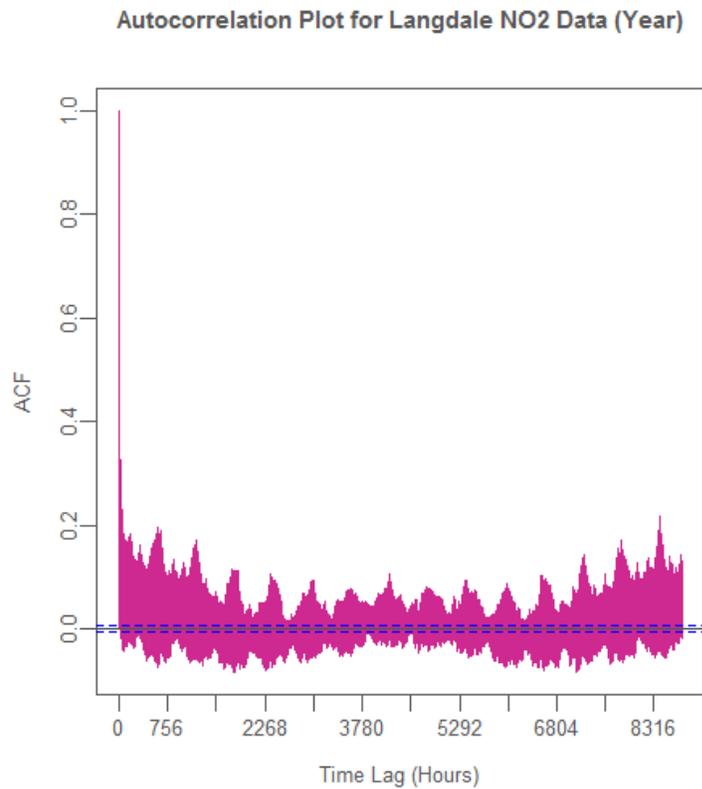
Autocorrelation Plot for Whistler NO<sub>2</sub> Data (Week)



Object E-20 'ACF graph of Whistler NO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'

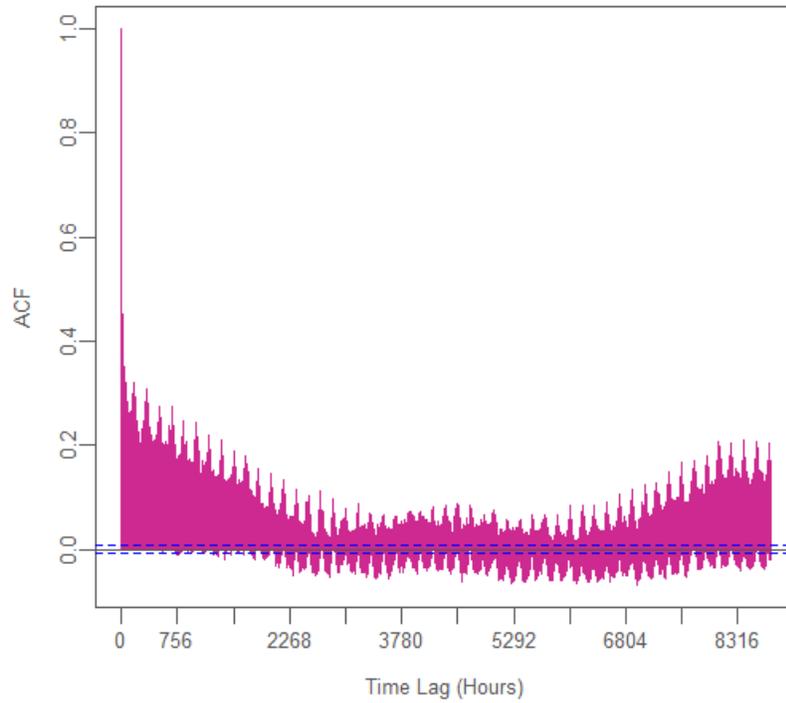


Object E-21 'ACF graph of Whistler Function Junction NO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'



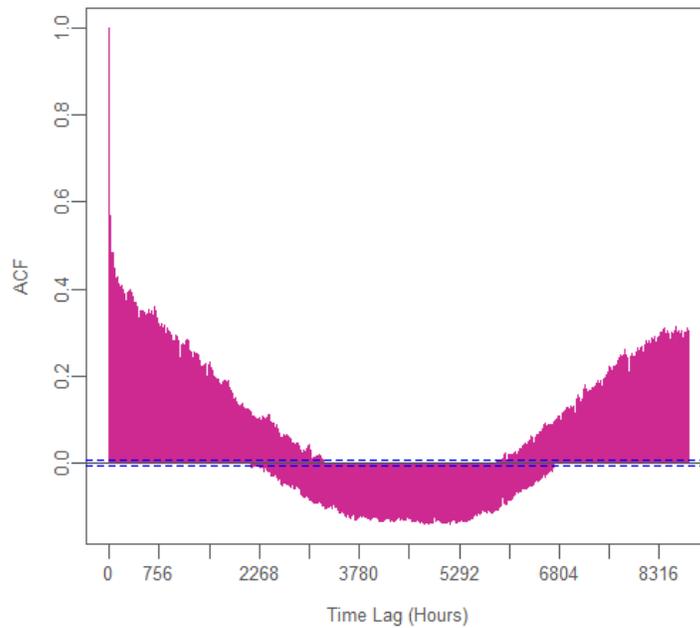
Object E-22 'ACF graph of Langdale NO<sub>2</sub> between 2001 and 2013, with time lag of up to one year'

**Autocorrelation Plot for Squamish NO<sub>2</sub> Data (Year)**

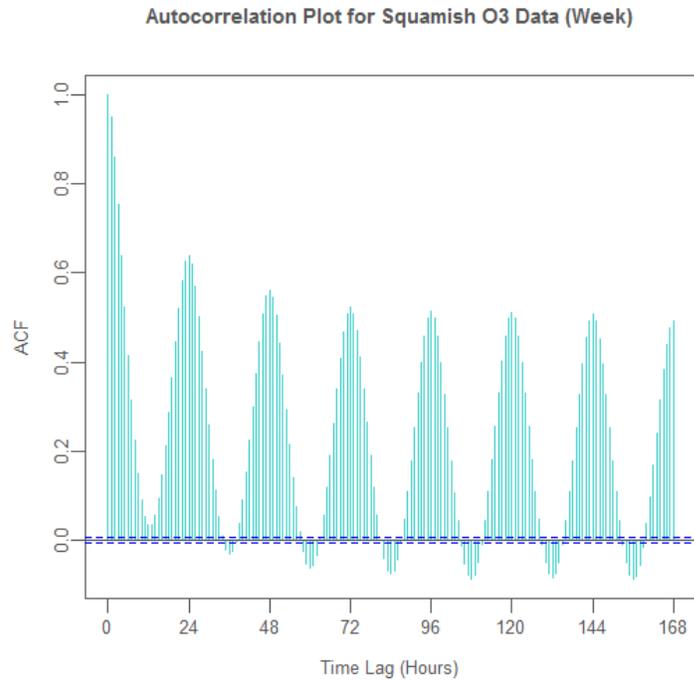


*Object E-23 'ACF graph of Squamish station NO<sub>2</sub> between 2001 and 2013, with time lag of up to one year'*

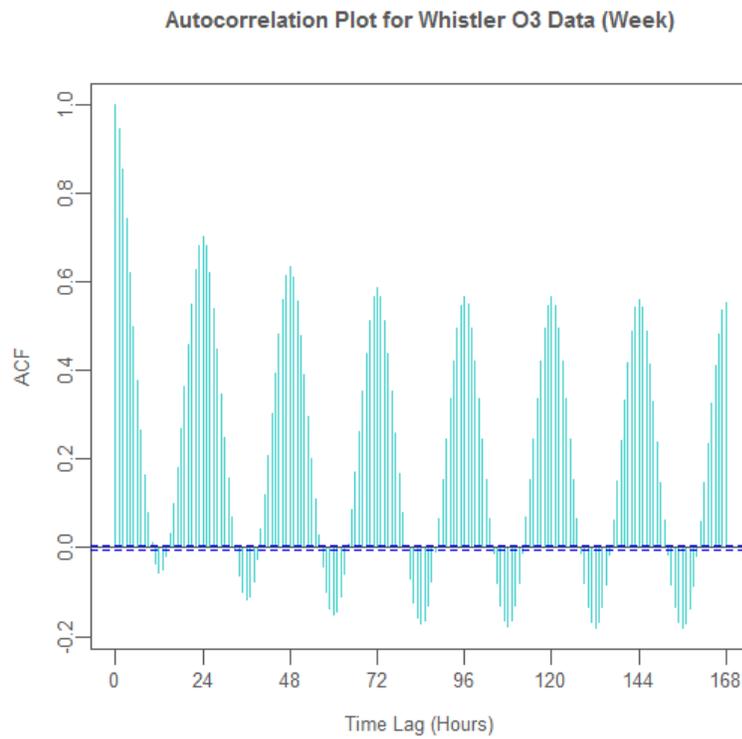
**Autocorrelation Plot for Whistler NO<sub>2</sub> Data (Year)**



*Object E-24 'ACF graph of Whistler station NO<sub>2</sub> between 2001 and 2013, with time lag of up to one year'*

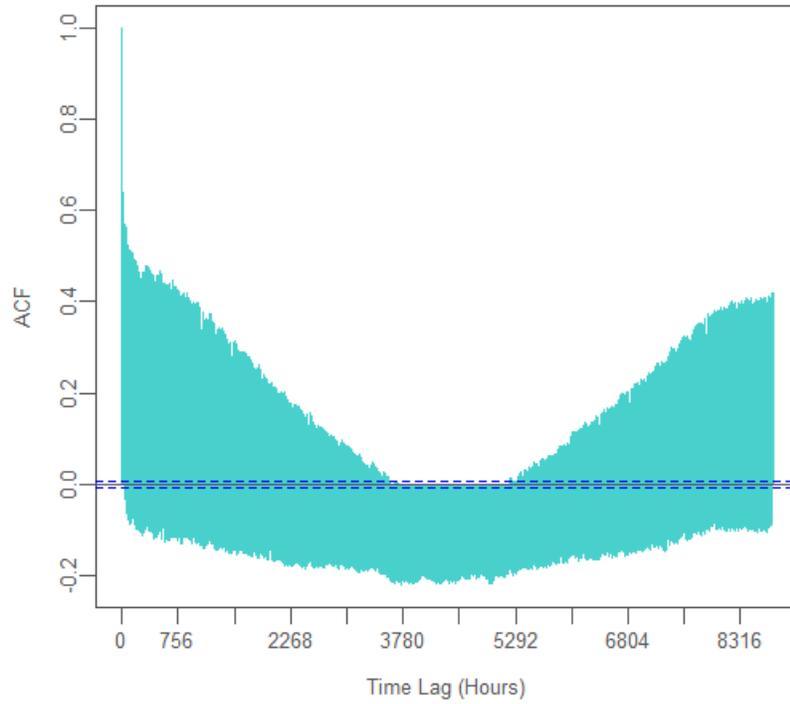


Object E-25 'ACF graph of Squamish station O<sub>3</sub> between 2001 and 2013, with time lag of up to one week'



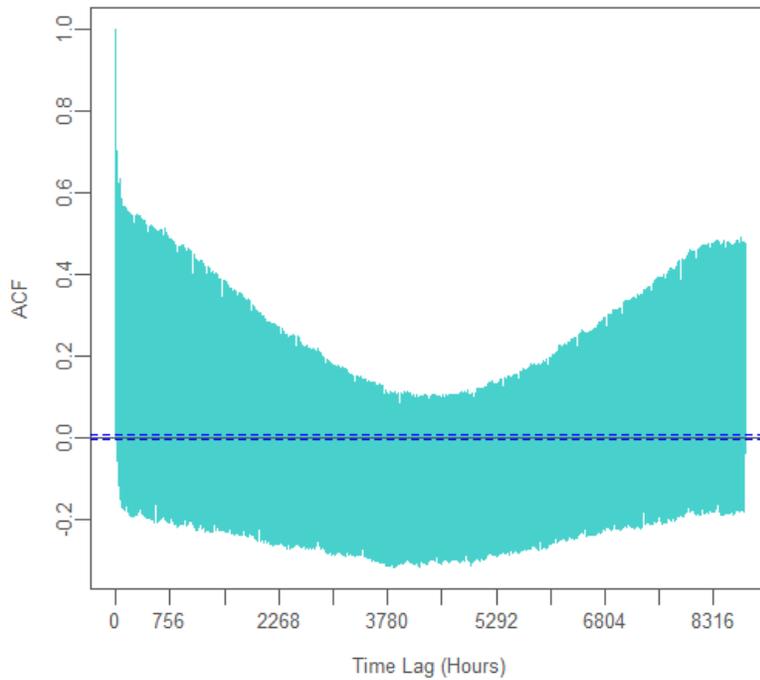
Object E-26 'ACF graph of Whistler station O<sub>3</sub> between 2001 and 2013, with time lag of up to one week'

**Autocorrelation Plot for Squamish O<sub>3</sub> Data (Year)**



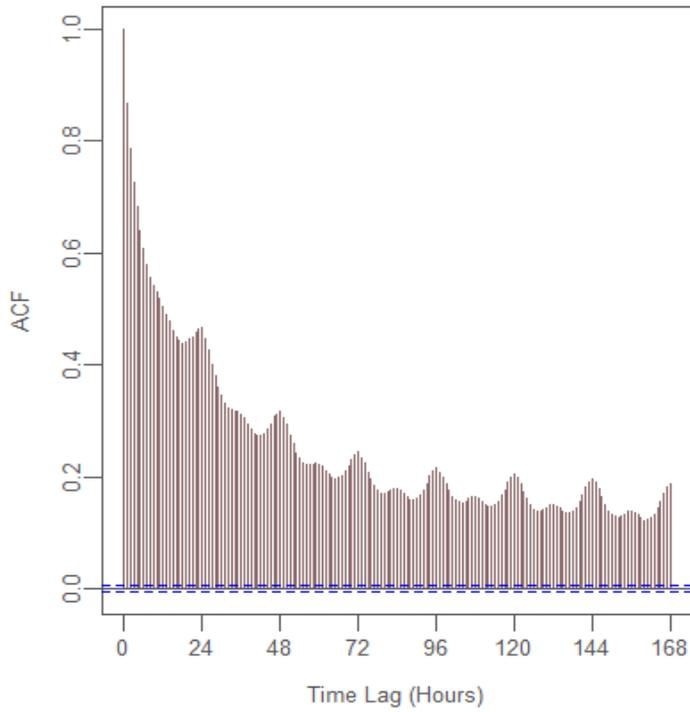
*Object E-27 'ACF graph of Squamish station O<sub>3</sub> between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Whistler O<sub>3</sub> Data (Year)**



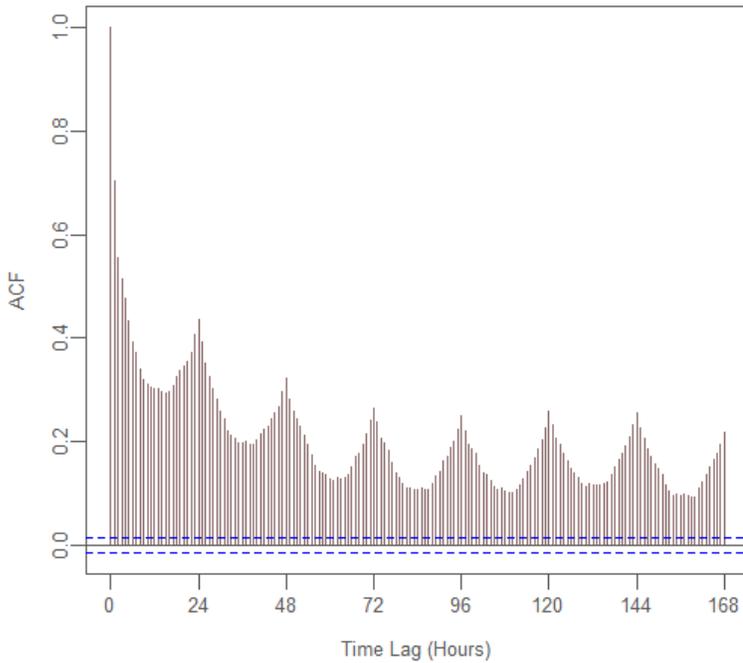
*Object E-28 'ACF graph of Squamish station O<sub>3</sub> between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Horseshoe Bay PM2.5 Data (Week)**



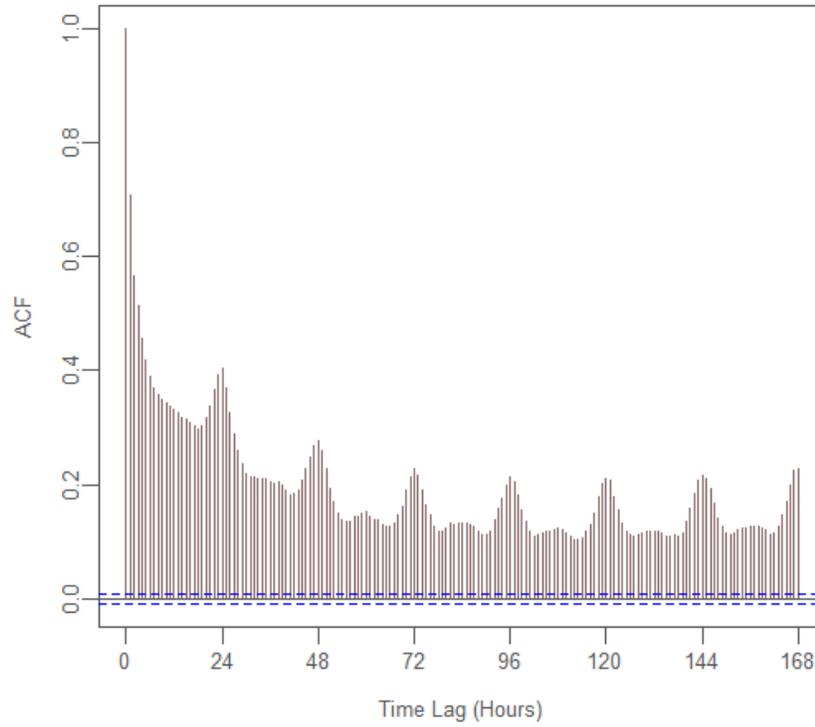
Object E-29 'ACF graph of Horseshoe Bay station PM<sub>2.5</sub> between 2001 and 2013, with time lag of up to one week'

**Autocorrelation Plot for Langdale PM2.5 BAM Data (Week)**



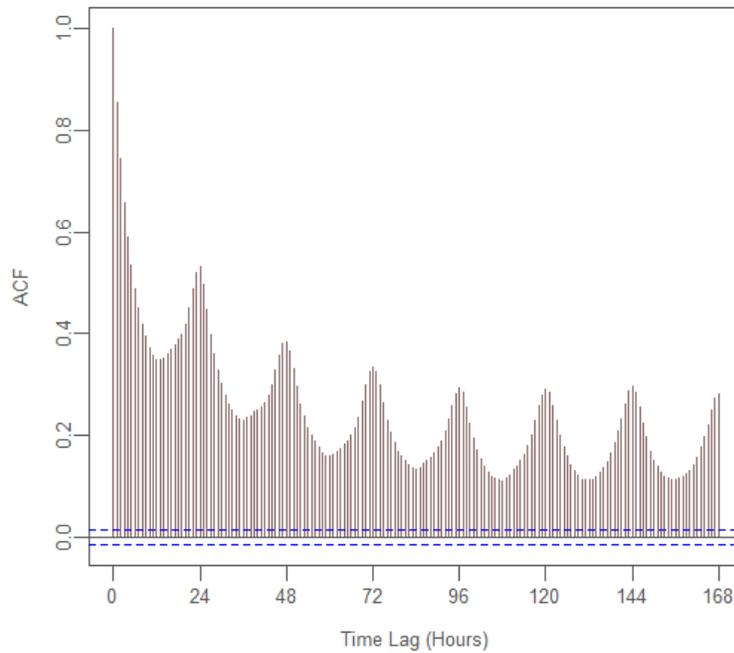
Object E-30 'ACF graph of Langdale station PM<sub>2.5</sub> between 2001 and 2013, with time lag of up to one week'

**Autocorrelation Plot for Squamish PM2.5 Data (Week)**



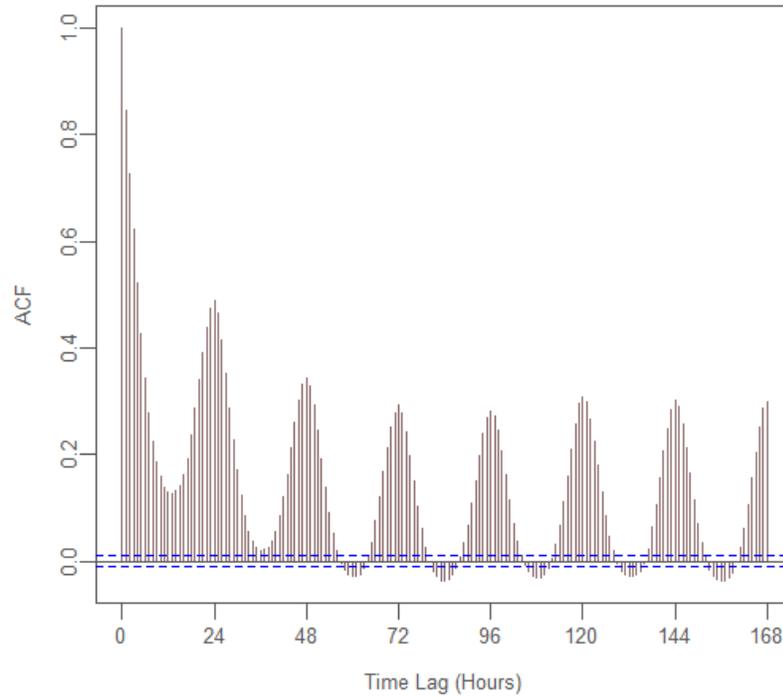
*Object E-31 'ACF graph of Squamish station PM<sub>2.5</sub> BAM between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Squamish PM2.5 TEOM Data (Week)**



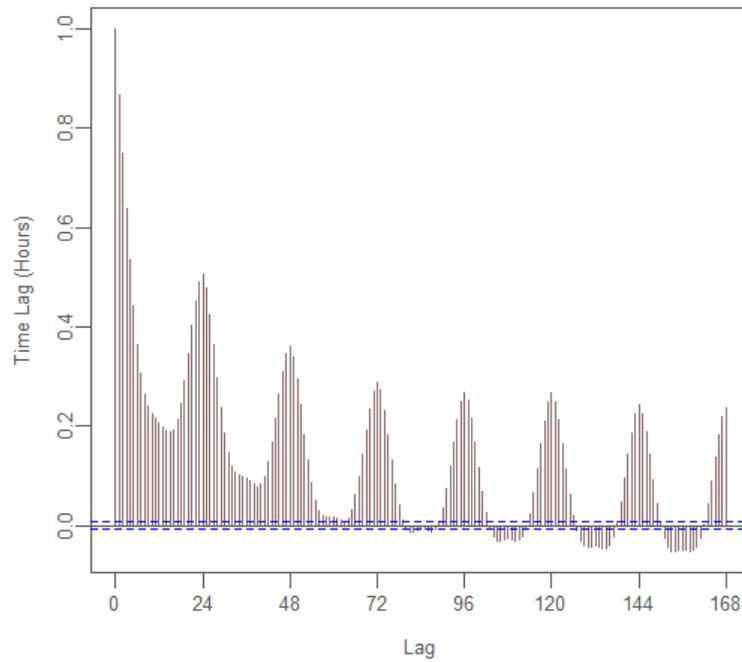
*Object E-32 'ACF graph of Squamish station PM<sub>2.5</sub> TEOM between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Whistler PM2.5 Data (Week)**



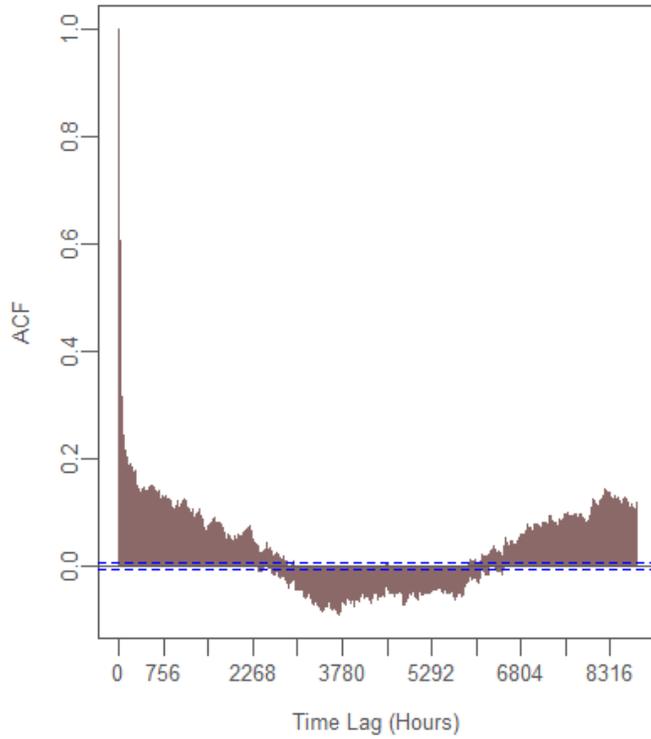
*Object E-33 'ACF graph of Whistler station PM<sub>2.5</sub> BAM between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Whistler PM2.5 TEOM Data (Week)**



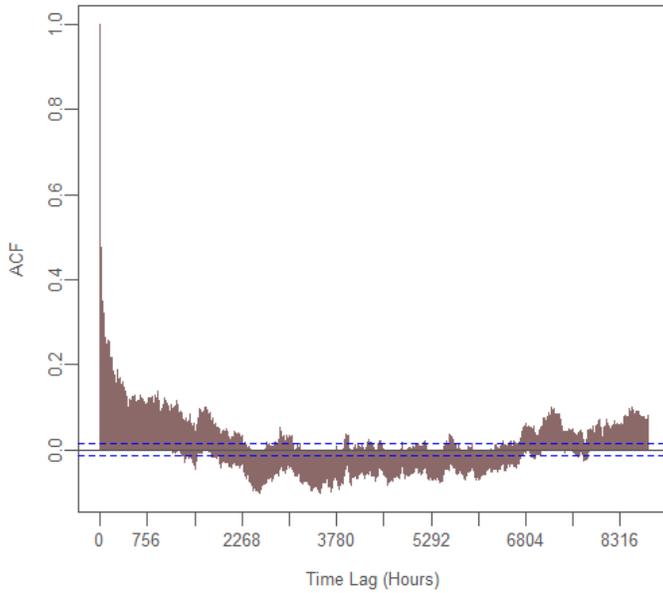
*Object E-34 'ACF graph of Whistler station PM<sub>2.5</sub> TEOM between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Horseshoe Bay PM2.5 Data (Year)**



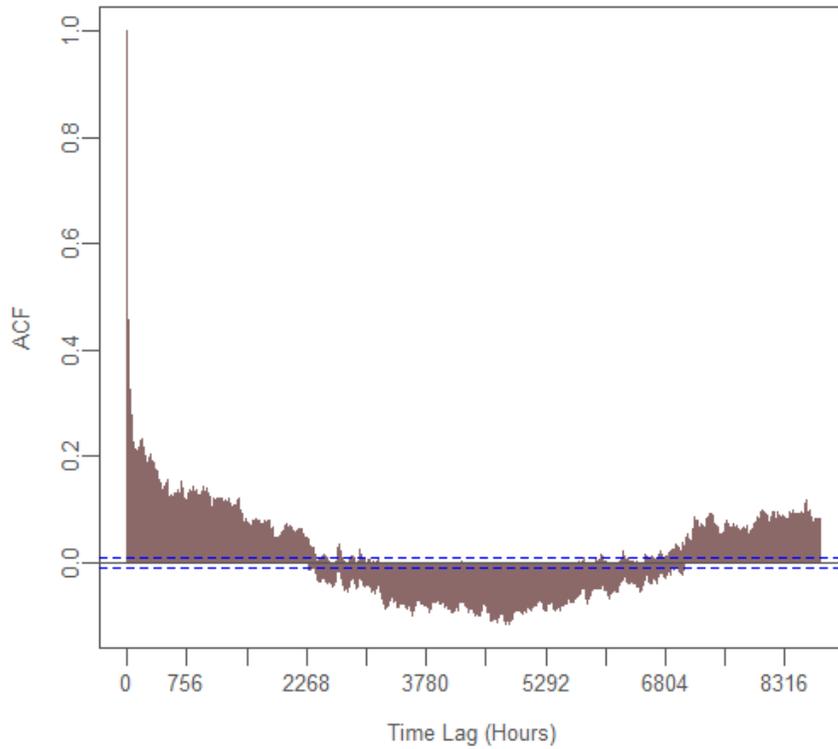
*Object E-35 'ACF graph of Langdale station PM<sub>2.5</sub> between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Langdale PM2.5 BAM Data (Year)**



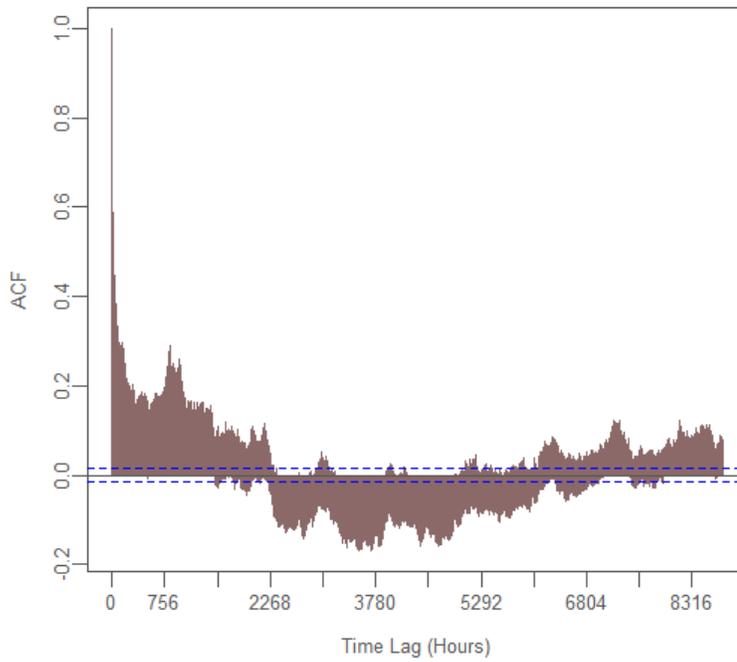
*Object E-36 'ACF graph of Langdale station PM<sub>2.5</sub> BAM between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Squamish PM2.5 Data (Year)**



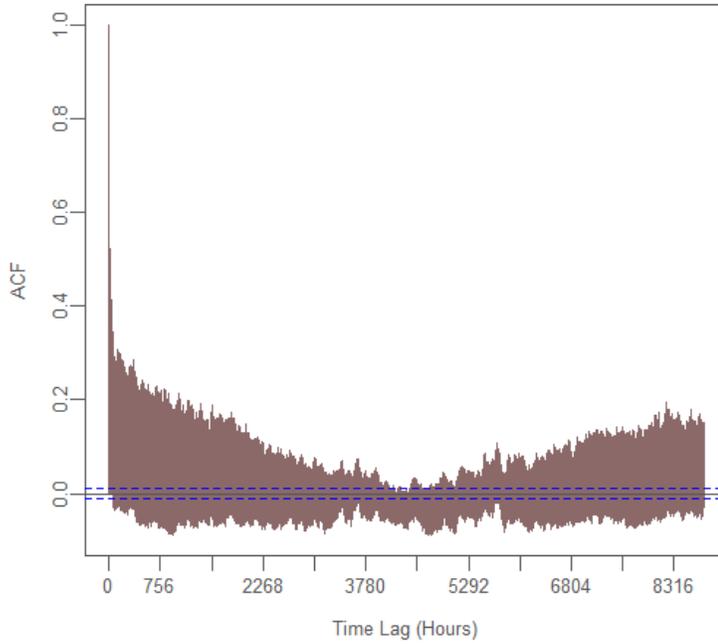
*Object E-37 'ACF graph of Squamish station PM<sub>2.5</sub> BAM between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Squamish PM2.5 TEOM Data (Year)**



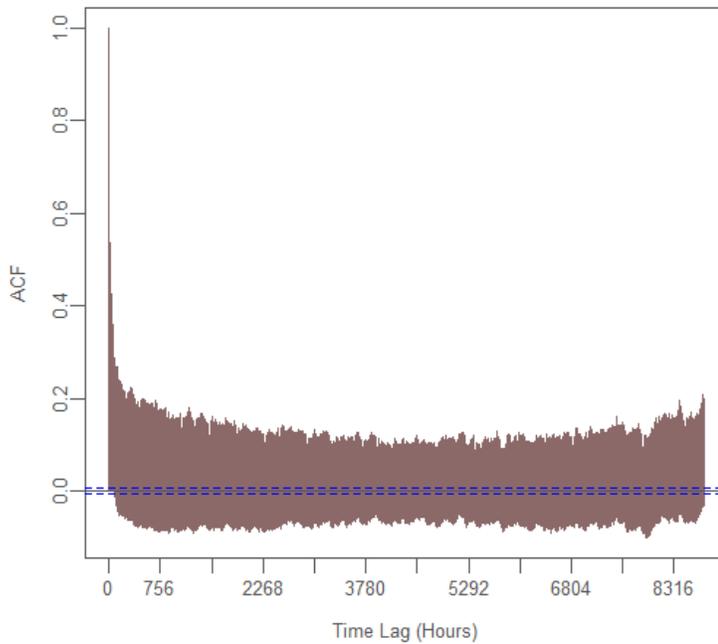
*Object E-38 'ACF graph of Squamish station PM<sub>2.5</sub> TEOM between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Whistler PM2.5 Data (Year)**

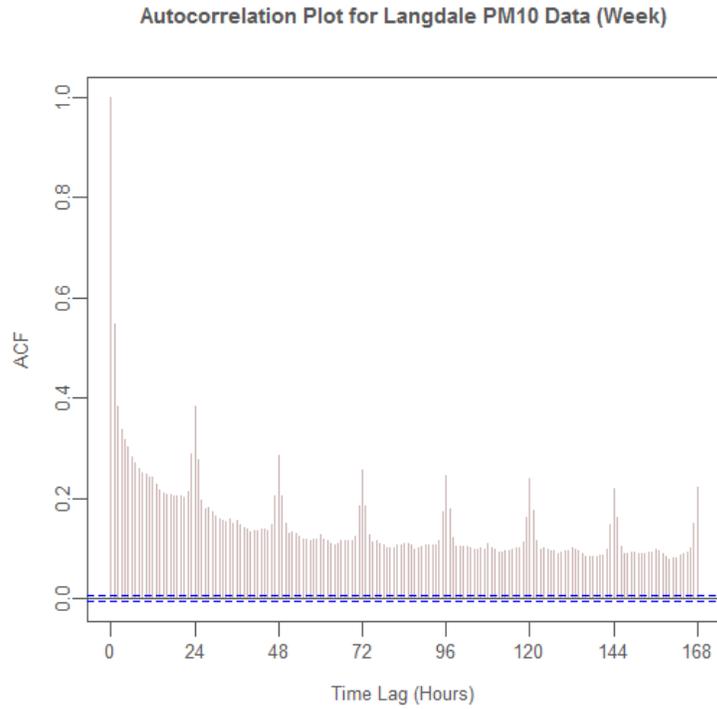


*Object E-39 'ACF graph of Whistler station PM<sub>2.5</sub> BAM between 2001 and 2013, with time lag of up to one year'*

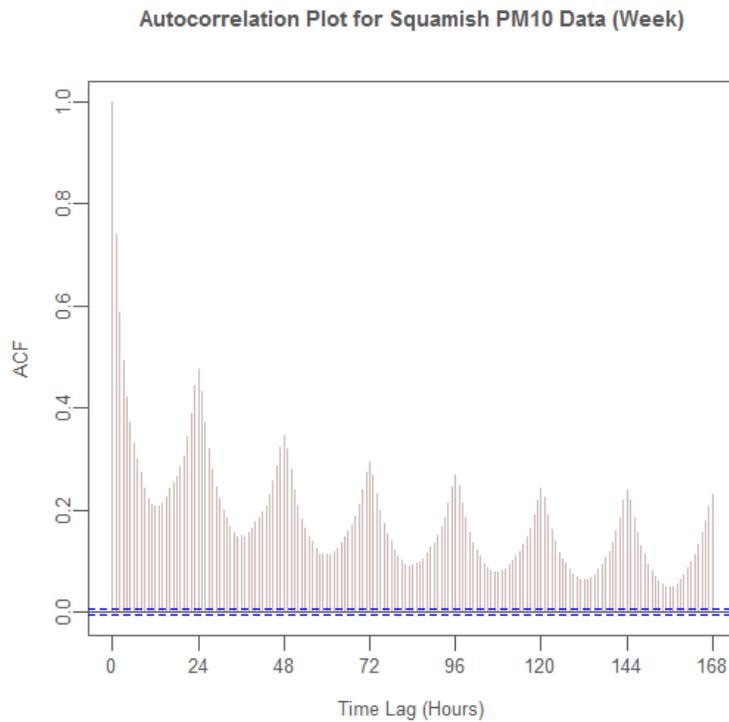
**Autocorrelation Plot for Whistler PM2.5 TEOM Data (Year)**



*Object E-40 'ACF graph of Whistler station PM<sub>2.5</sub> TEOM between 2001 and 2013, with time lag of up to one year'*

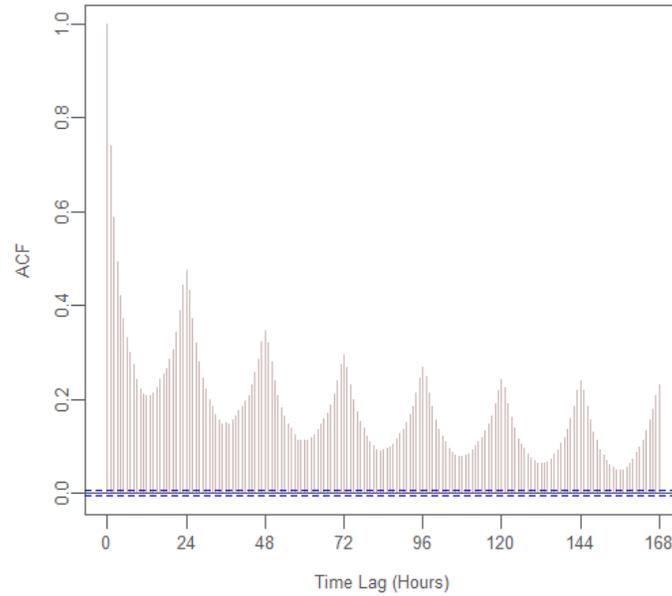


Object E-41 'ACF graph of Langdale station PM<sub>10</sub> between 2001 and 2013, with time lag of up to one week'



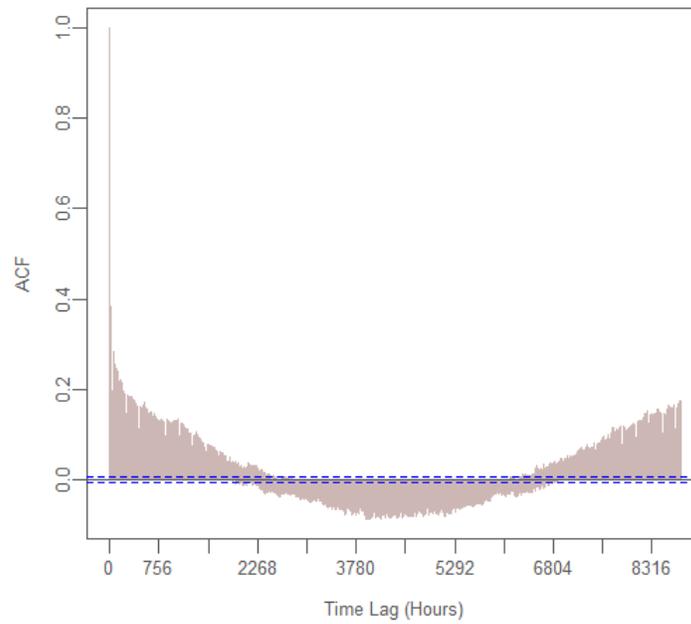
Object E-41 'ACF graph of Langdale station PM<sub>10</sub> between 2001 and 2013, with time lag of up to one week'

Autocorrelation Plot for Squamish PM10 Data (Week)

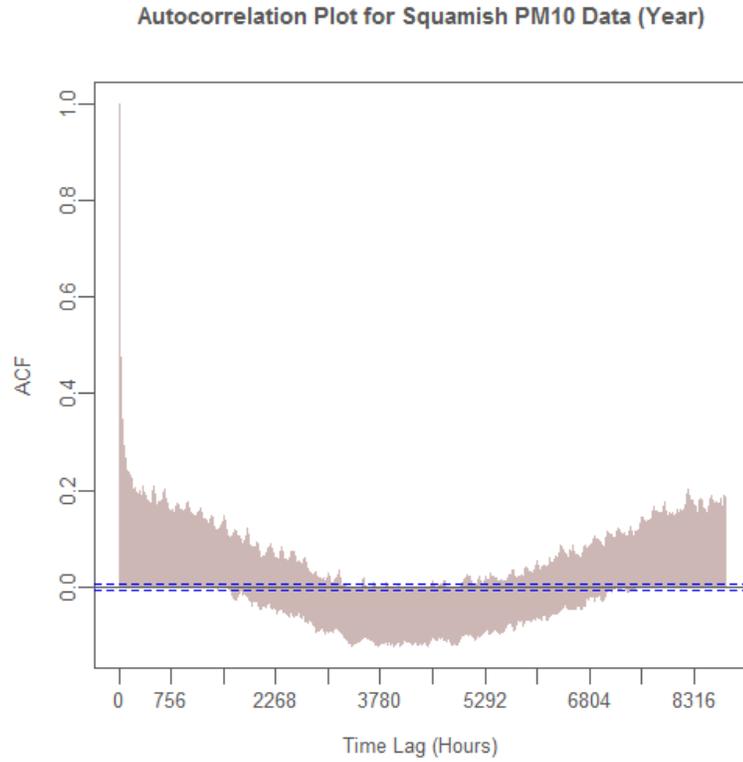


Object E-42 'ACF graph of Squamish station PM<sub>10</sub> between 2001 and 2013, with time lag of up to one week'

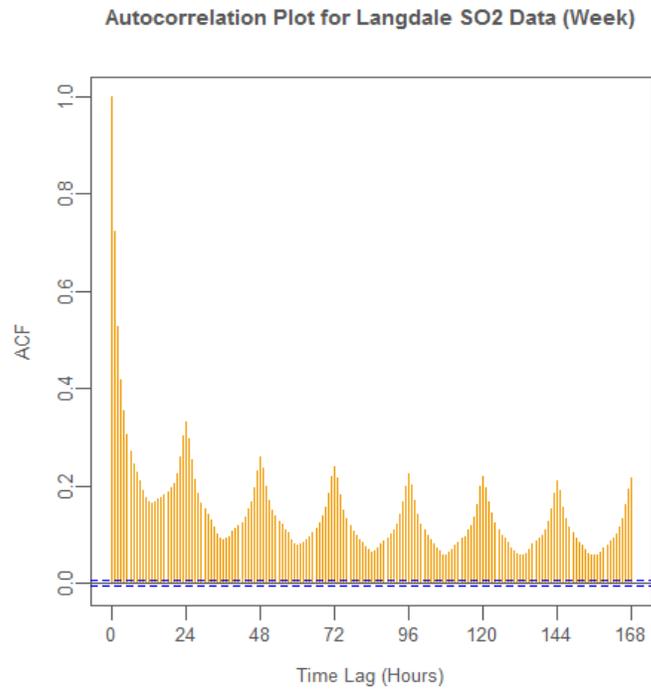
Autocorrelation Plot for Langdale PM10 Data (Year)



Object E-43 'ACF graph of Langdale station PM<sub>10</sub> between 2001 and 2013, with time lag of up to one year'

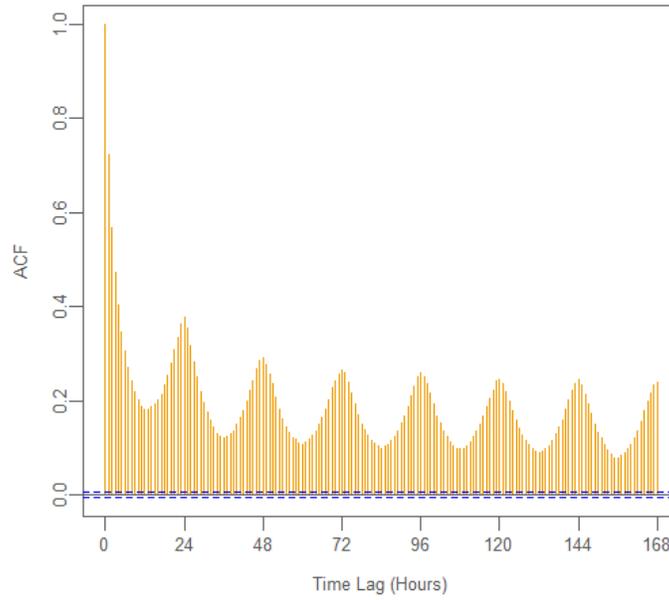


Object E-44 'ACF graph of Squamish station PM<sub>10</sub> between 2001 and 2013, with time lag of up to one year'



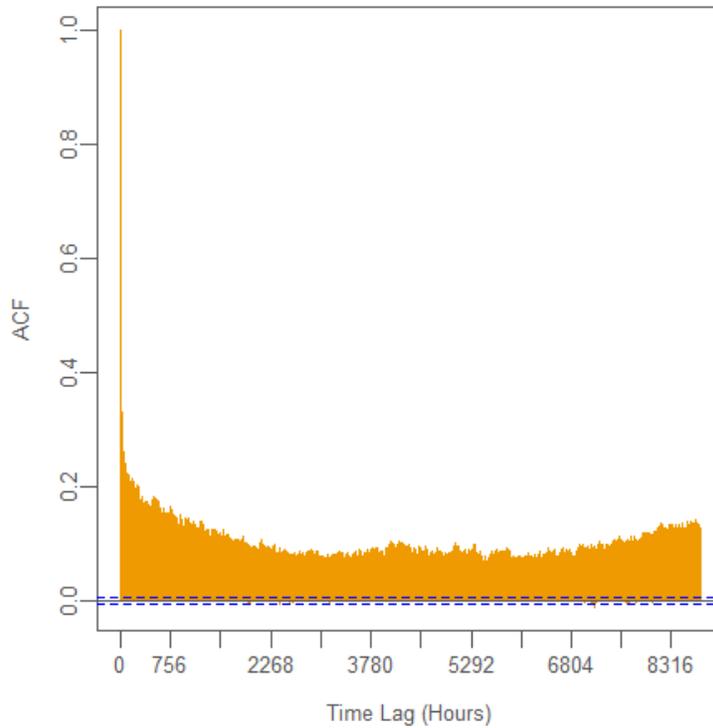
Object E-45 'ACF graph of Langdale station SO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'

**Autocorrelation Plot for Squamish SO<sub>2</sub> Data (Week)**



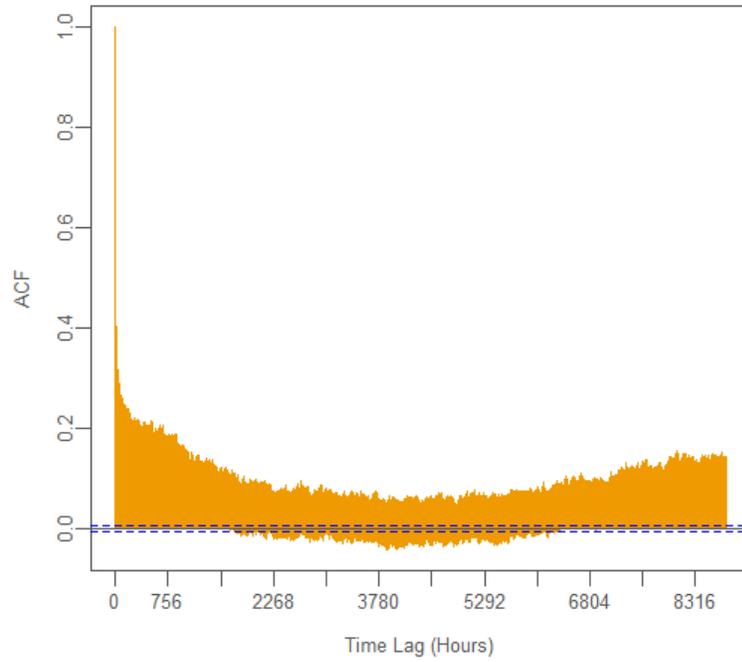
*Object E-46 'ACF graph of Squamish station SO<sub>2</sub> between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Langdale SO<sub>2</sub> Data (Year)**



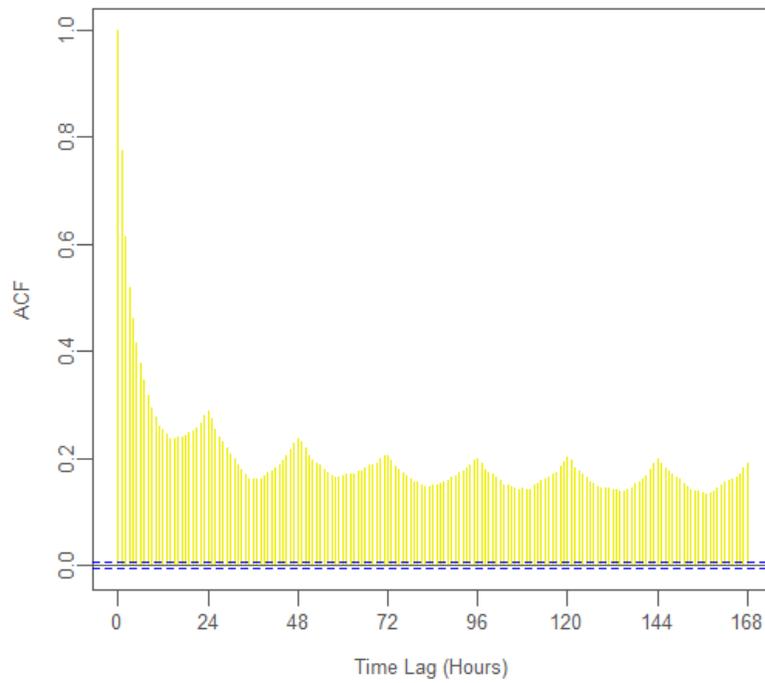
*Object E-47 'ACF graph of Langdale station SO<sub>2</sub> between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Squamish SO<sub>2</sub> Data (Year)**



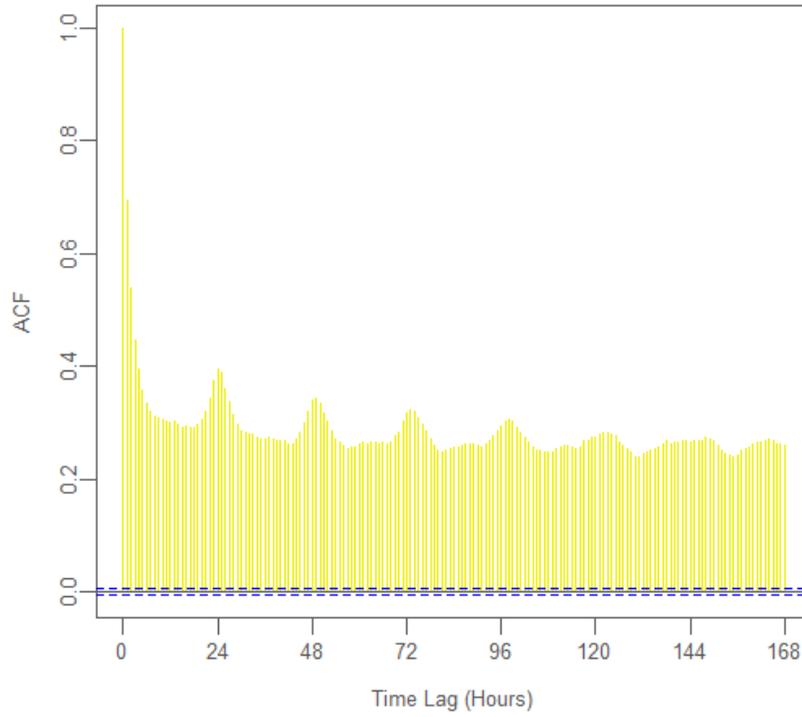
*Object E-48 'ACF graph of Squamish station SO<sub>2</sub> between 2001 and 2013, with time lag of up to one year'*

**Autocorrelation Plot for Langdale TRS Data (Week)**



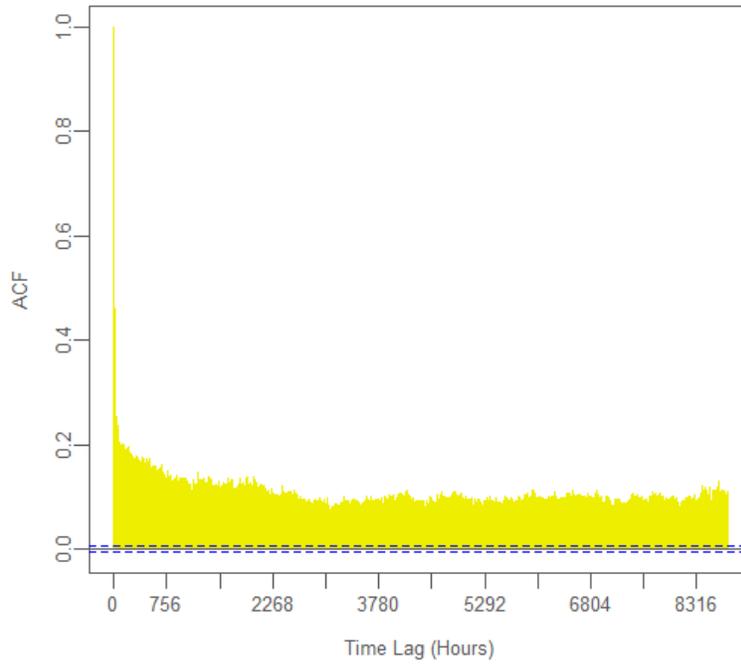
*Object E-49 'ACF graph of Langdale station TRS between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Squamish TRS Data (Week)**

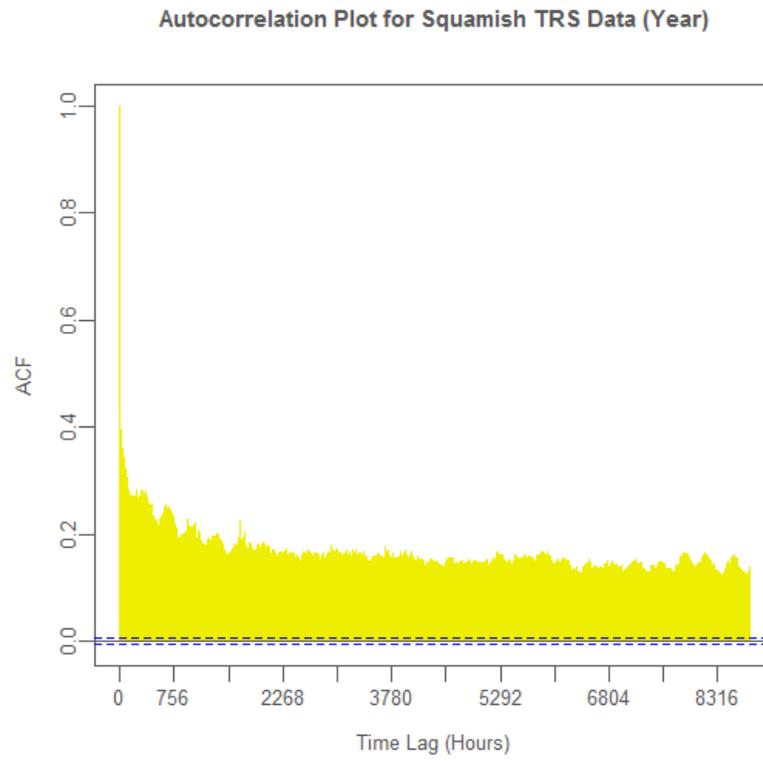


*Object E-50 'ACF graph of Squamish station TRS between 2001 and 2013, with time lag of up to one week'*

**Autocorrelation Plot for Langdale TRS Data (Year)**

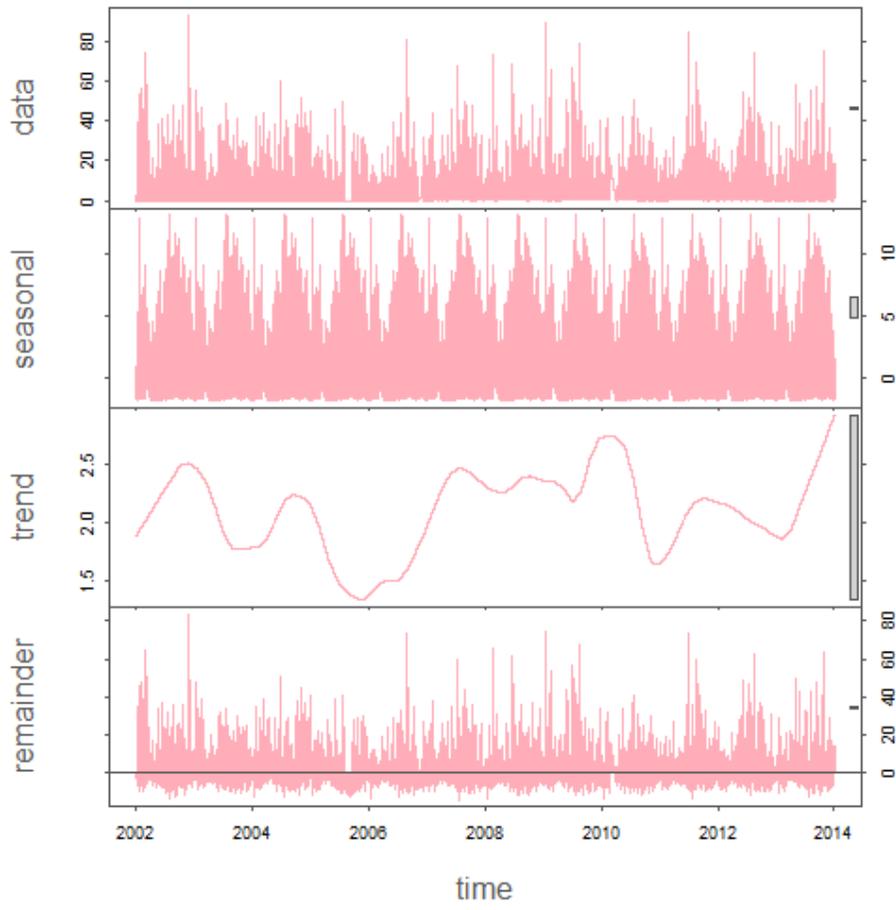


*Object E-51 'ACF graph of Langdale station TRS between 2001 and 2013, with time lag of up to one year'*



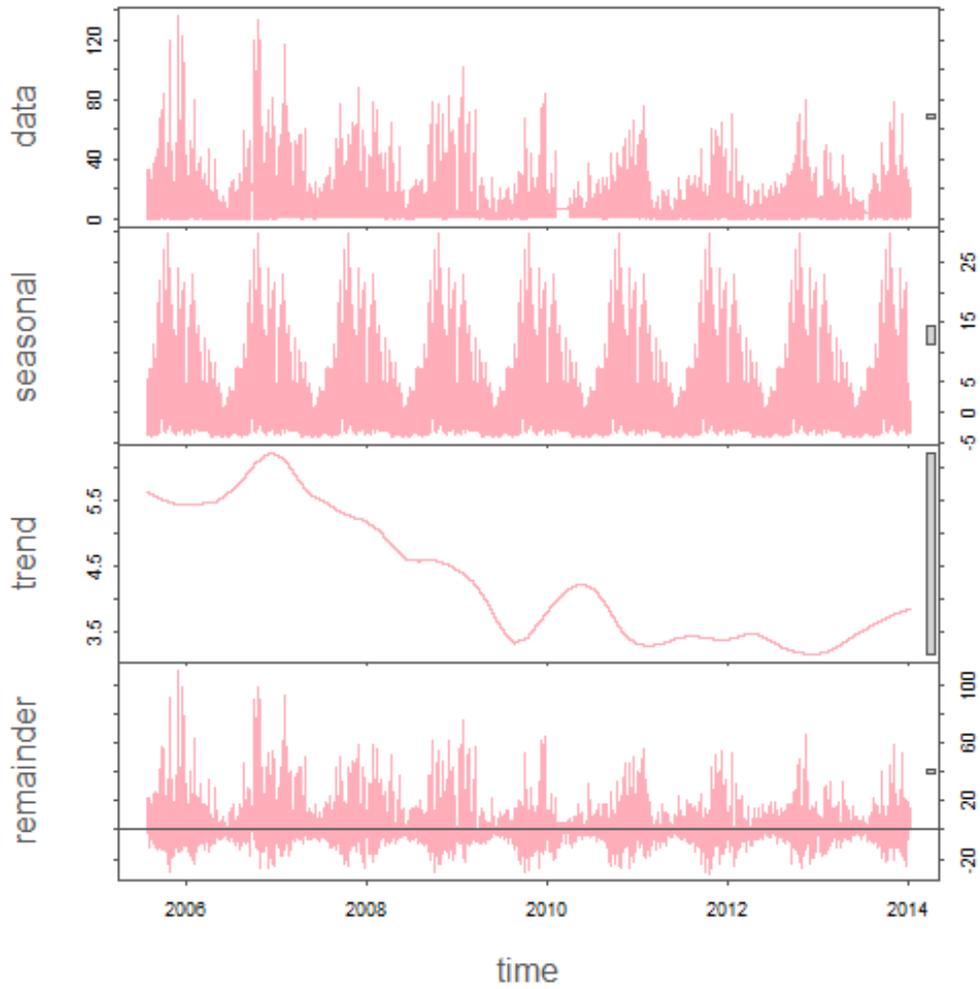
*Object E-52 'ACF graph of Squamish station TRS between 2001 and 2013, with time lag of up to one year'*

### STL Chart for Langdale NO



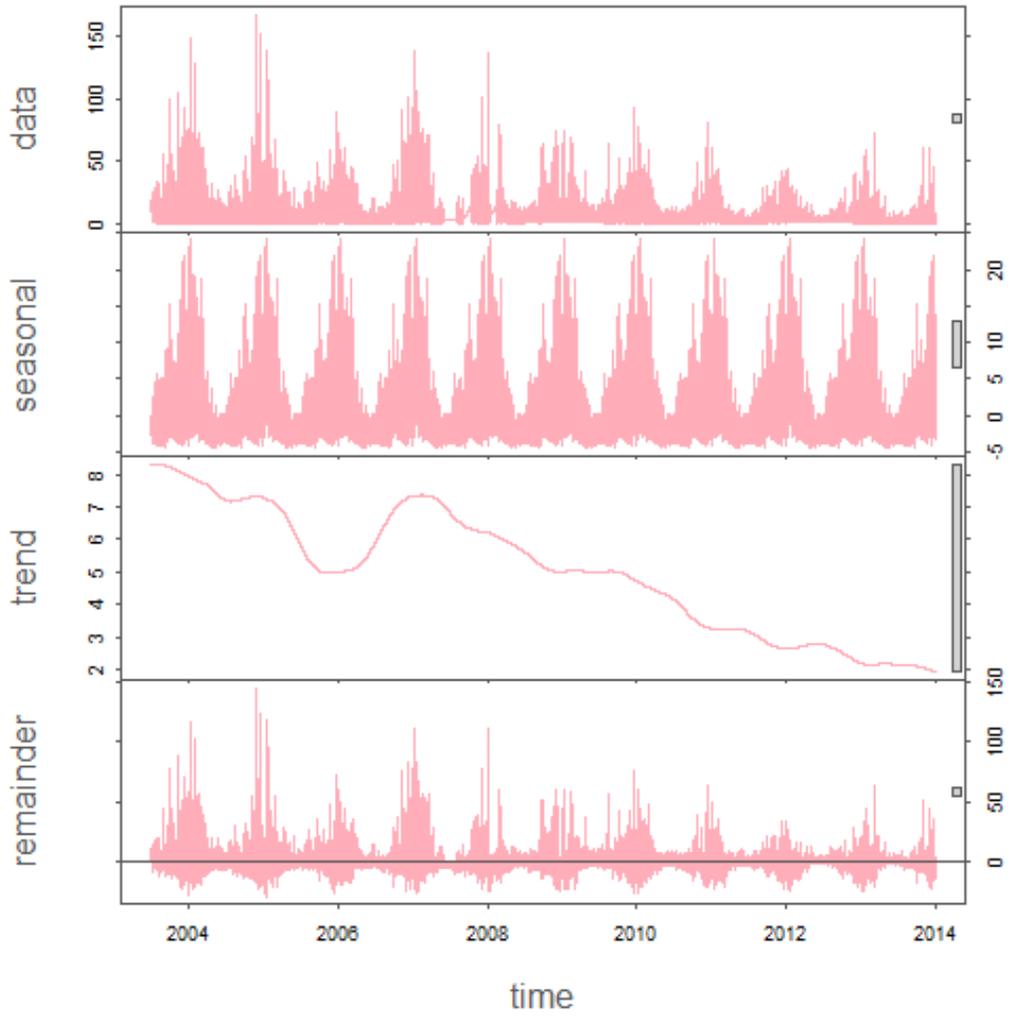
Object E-53 'STL chart for Langdale NO, 2002 to 2013'

### STL Chart for Squamish NO



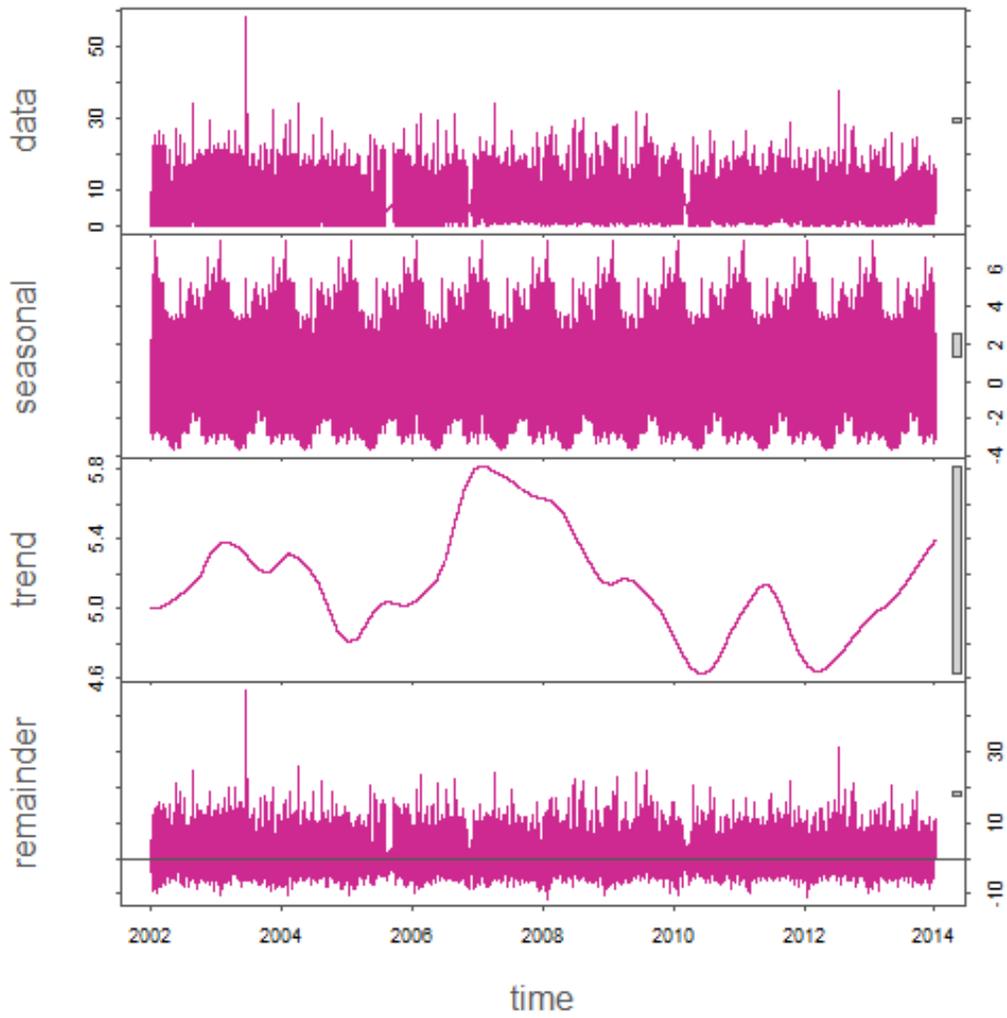
Object E-54 'STL chart for Squamish NO, 2002 to 2013'

### STL Chart for Whistler NO



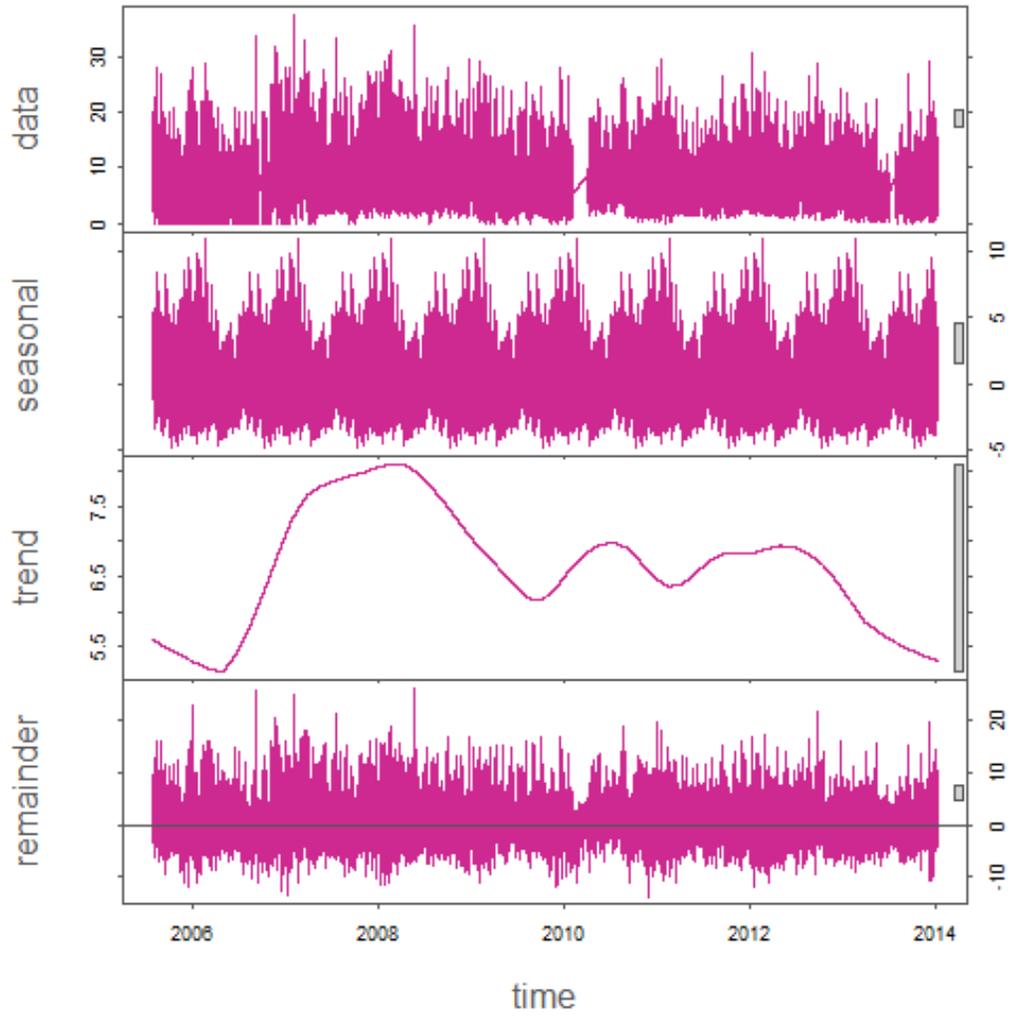
Object E-55 'STL chart for Whistler NO, 2002 to 2013'

### STL Chart for Langdale NO2



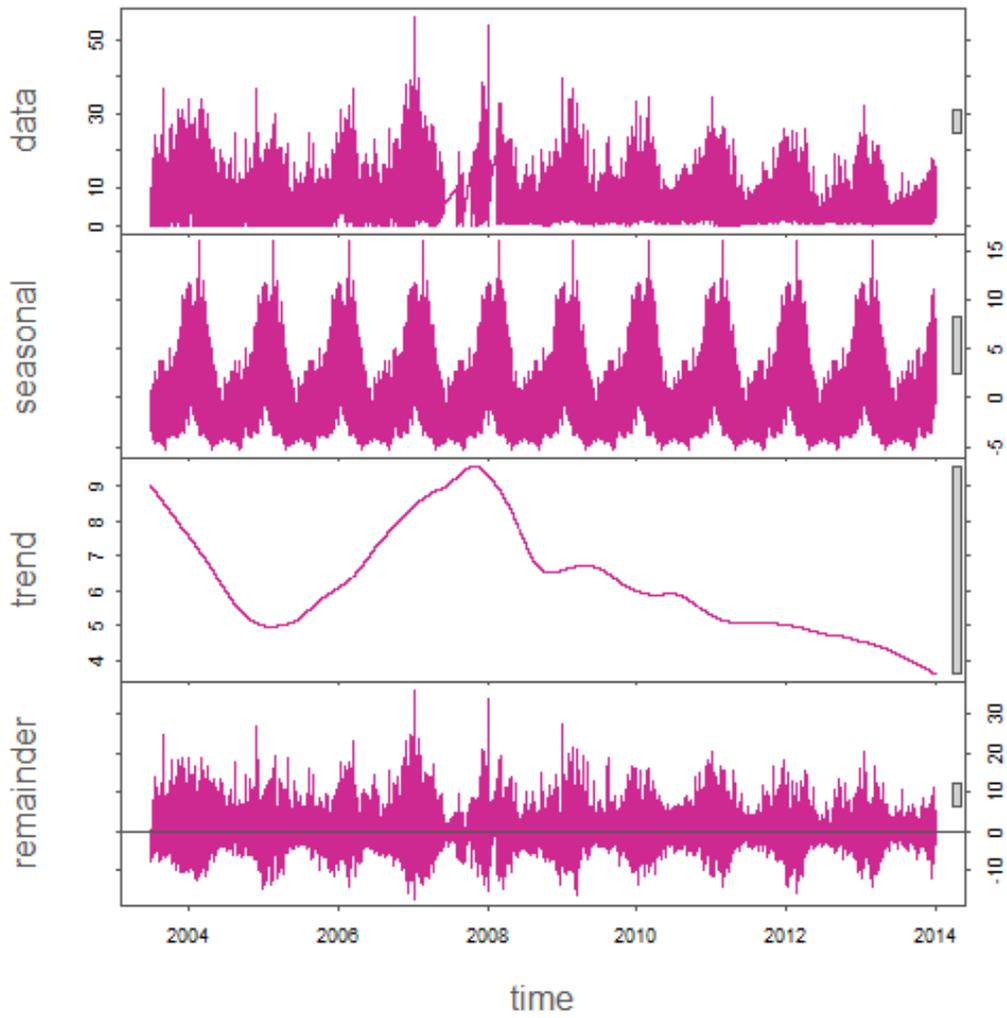
Object E-56 'STL chart for Langdale NO<sub>2</sub>, 2002 to 2013'

### STL Chart for Squamish NO2



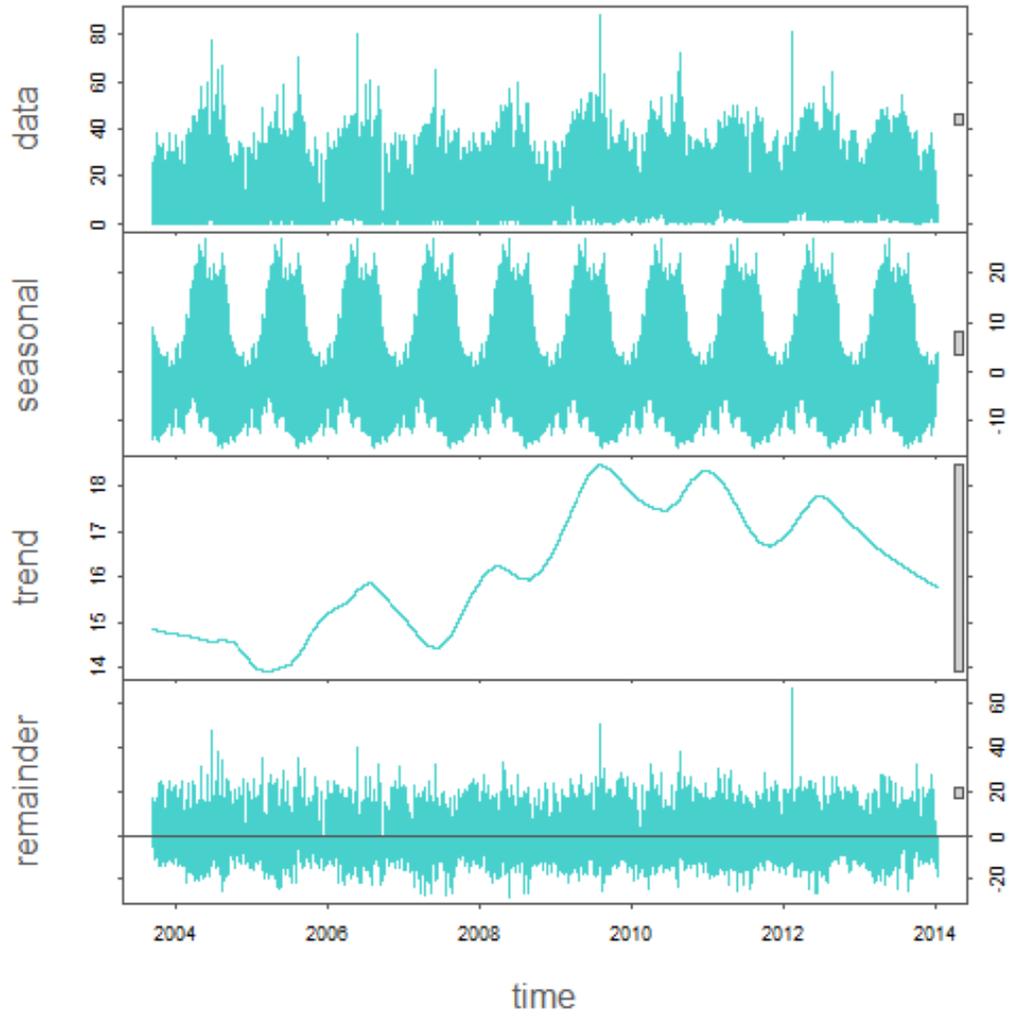
Object E-57 'STL chart for Squamish NO<sub>2</sub>, 2002 to 2013'

### STL Chart for Whistler NO2



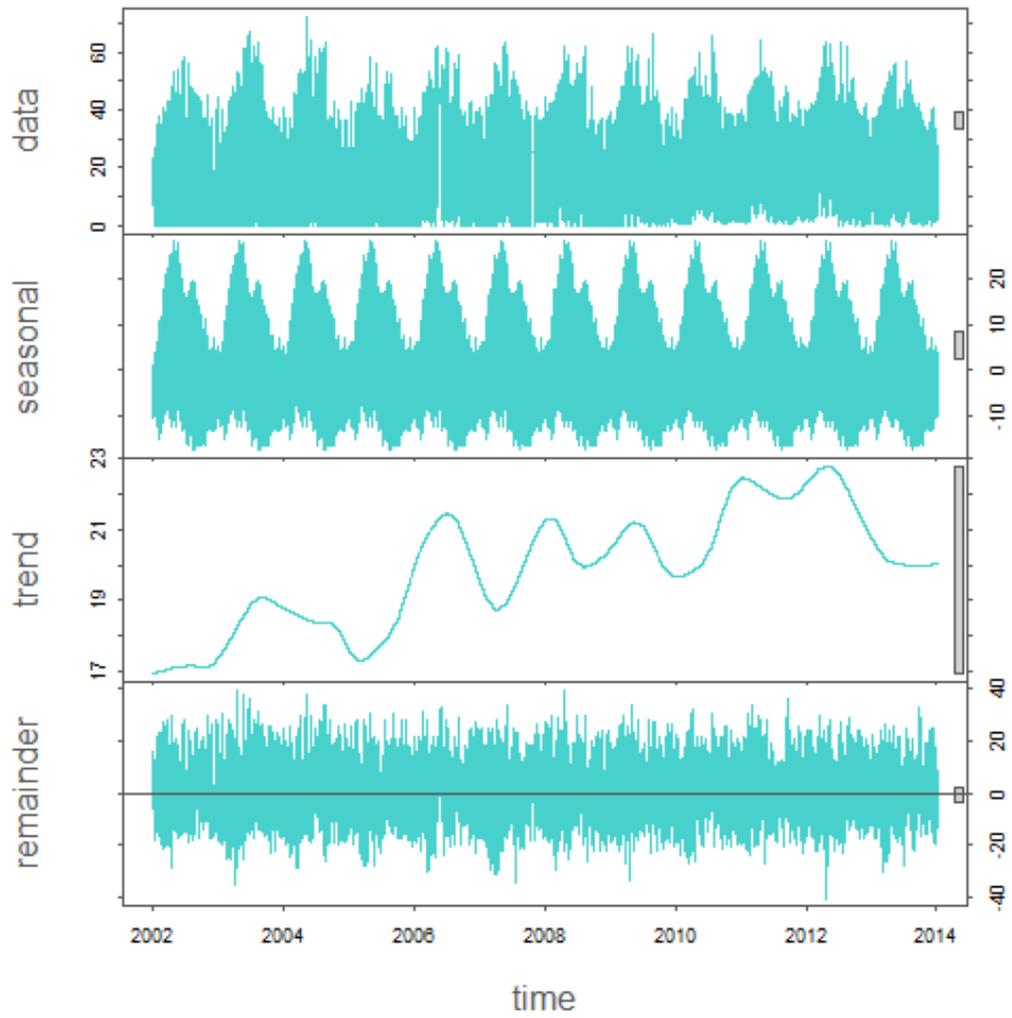
Object E-58 'STL chart for Whistler NO<sub>2</sub>, 2002 to 2013'

### STL Chart for Squamish O<sub>3</sub>



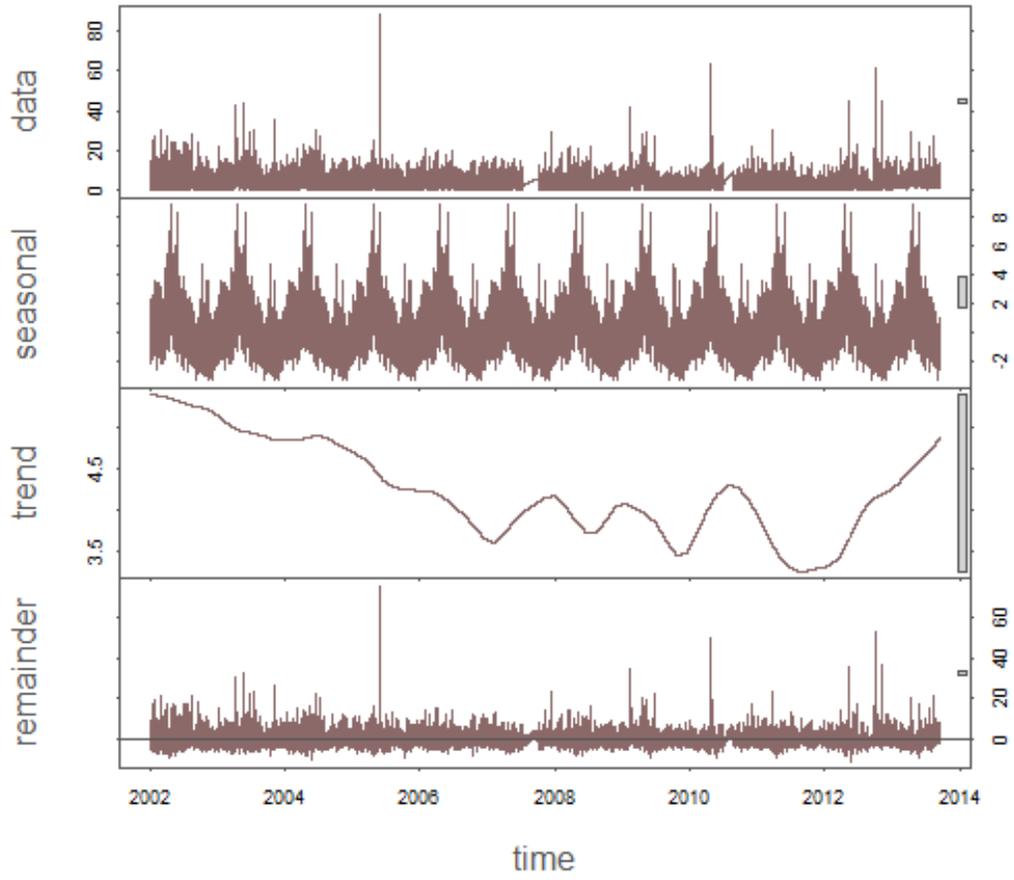
Object E-59 'STL chart for Squamish O<sub>3</sub>, 2004 to 2013'

### STL Chart for Whistler O3



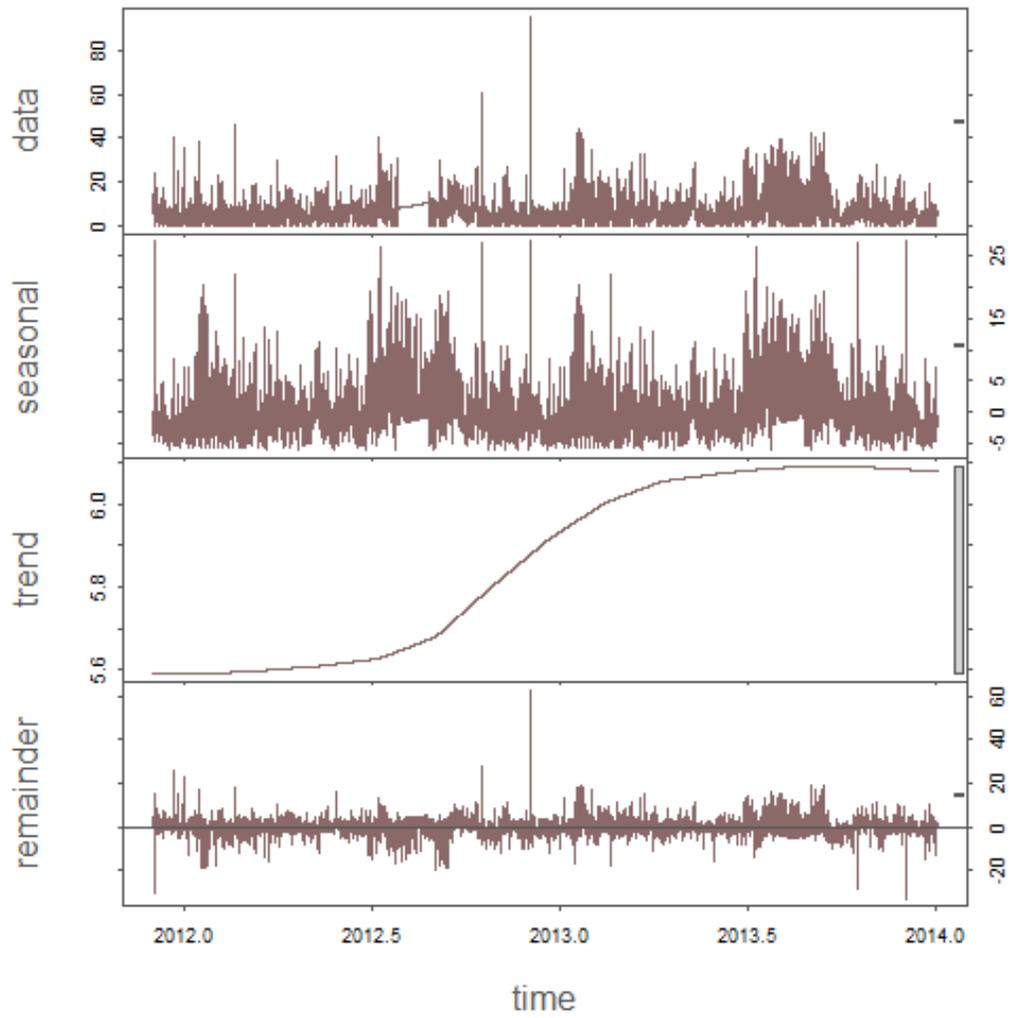
Object E-60 'STL chart for Whistler O<sub>3</sub>, 2002 to 2013'

### STL Chart for Horseshoe Bay PM2.5 (TEOM)



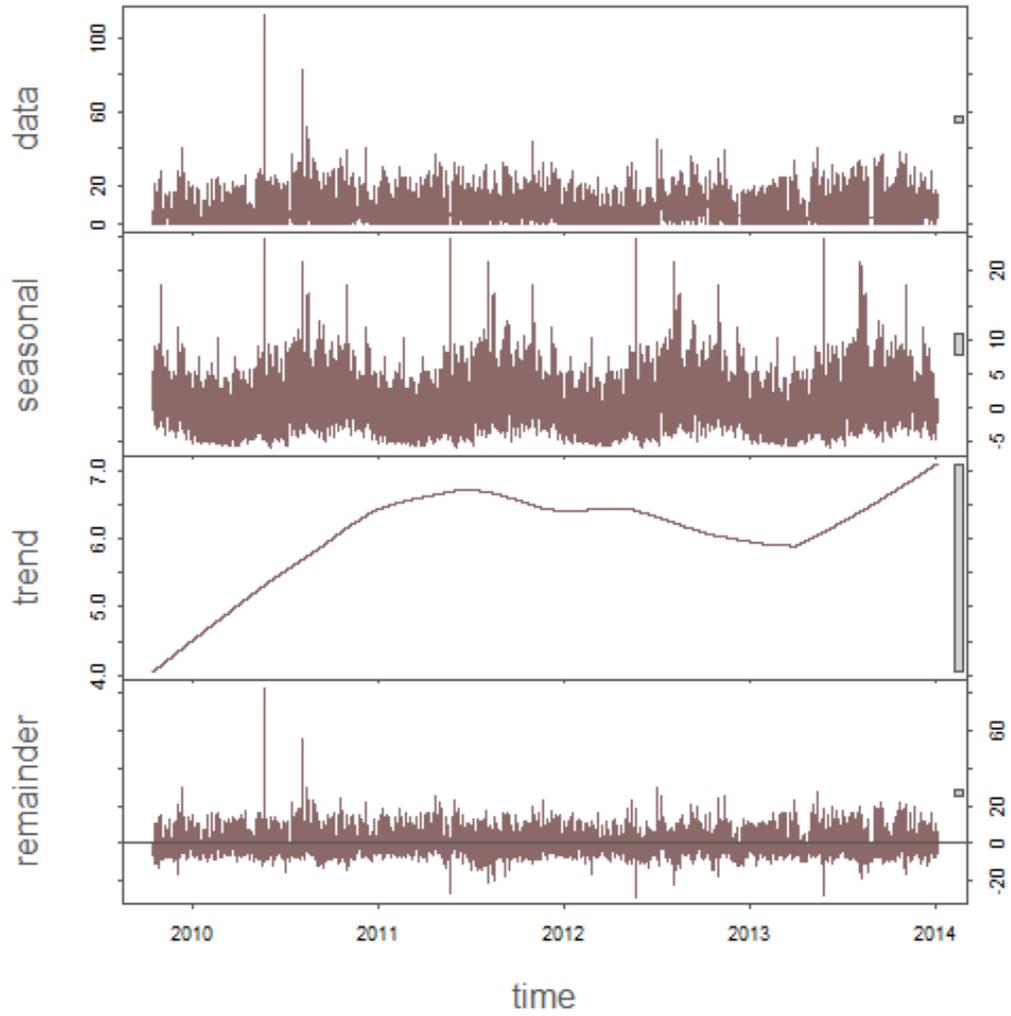
Object E-61 'STL chart for Horseshoe Bay<sub>PM2.5</sub> TEOM 2002 to 2013'

### STL Chart for Langdale PM2.5 (BAM)



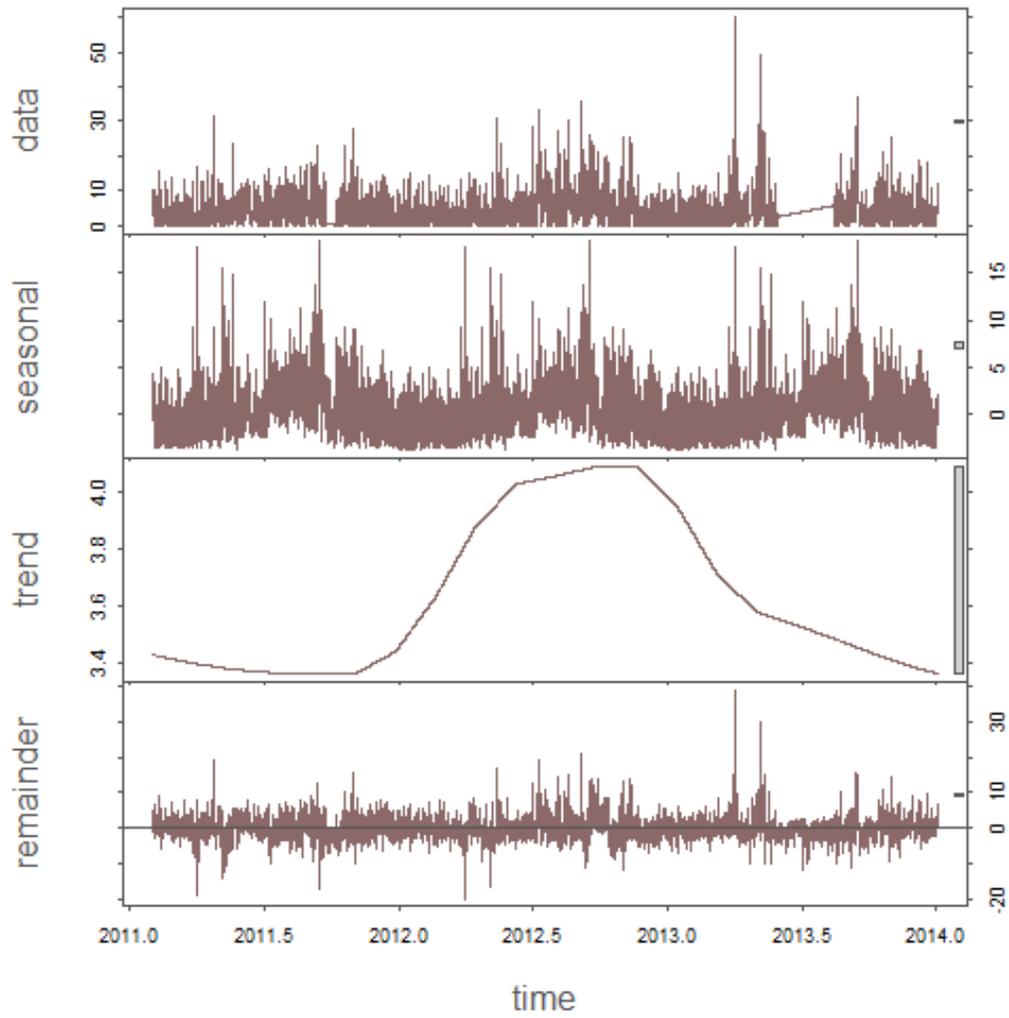
Object E-62 'STL chart for Langdale PM<sub>PM2.5</sub> BAM 2012 to 2013'

### STL Chart for Squamish PM2.5



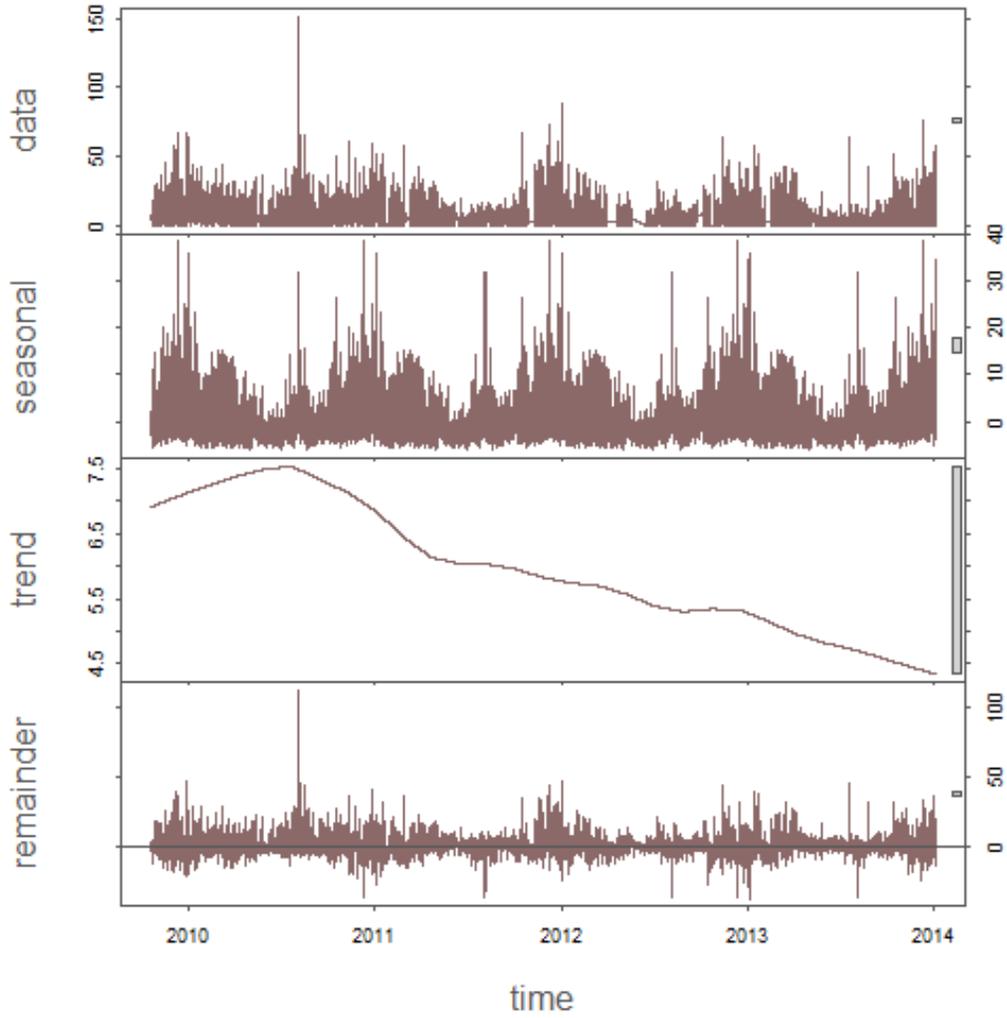
Object E-63 'STL chart for Squamish PM<sub>PM2.5</sub> BAM 2010 to 2013'

### STL Chart for Squamish PM2.5 (TEOM)



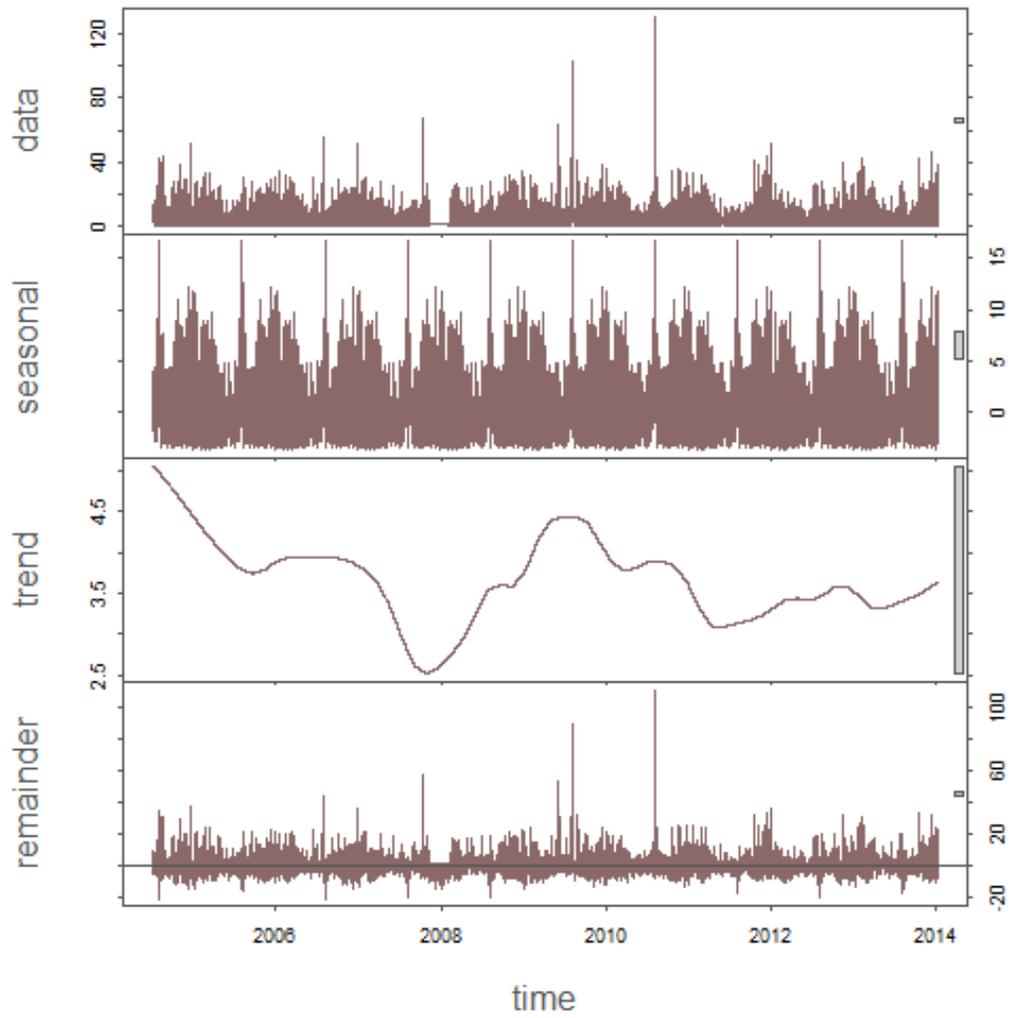
Object E-64 'STL chart for Squamish PM<sub>PM2.5</sub> TEOM 2011 to 2013'

### STL Chart for Whistler PM2.5



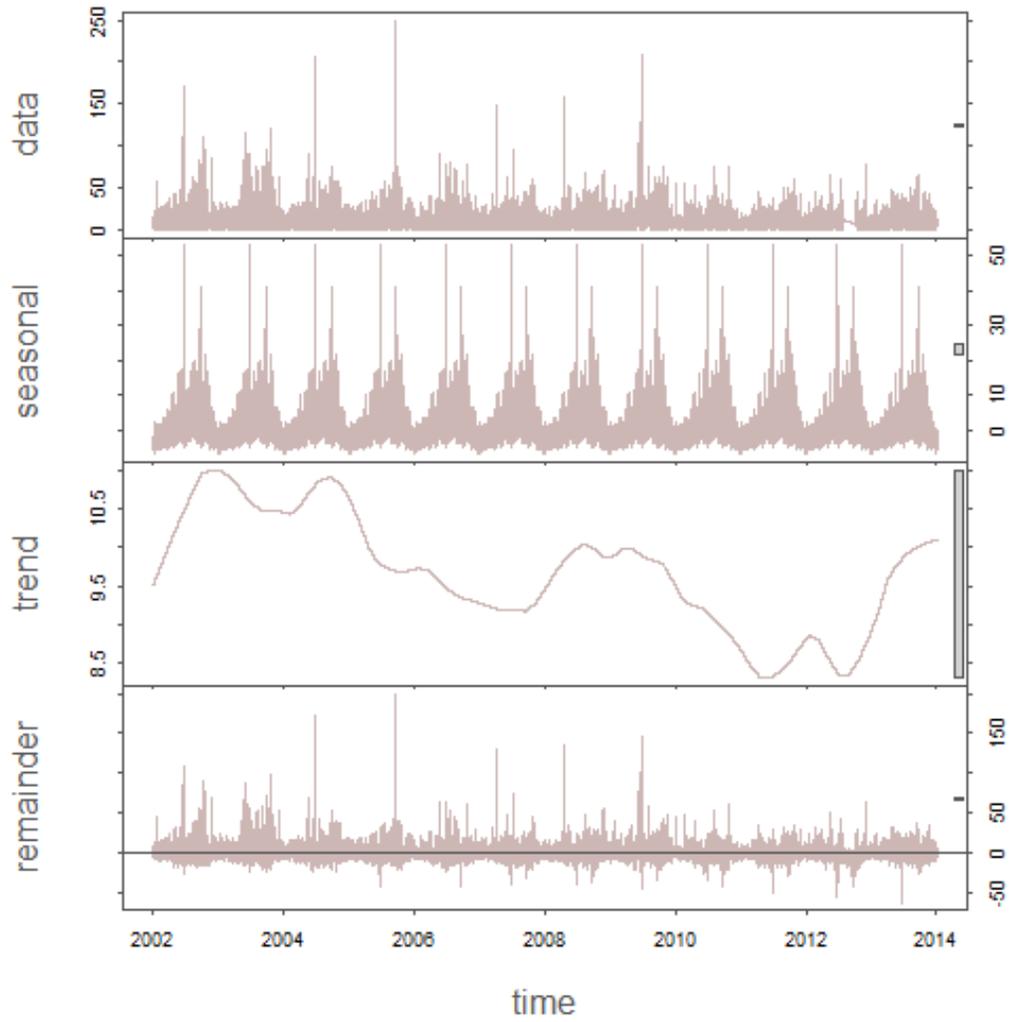
Object E-65 'STL chart for Whistler PM<sub>PM2.5</sub> BAM 2010 to 2013'

### STL Chart for Whistler PM2.5 (TEOM)



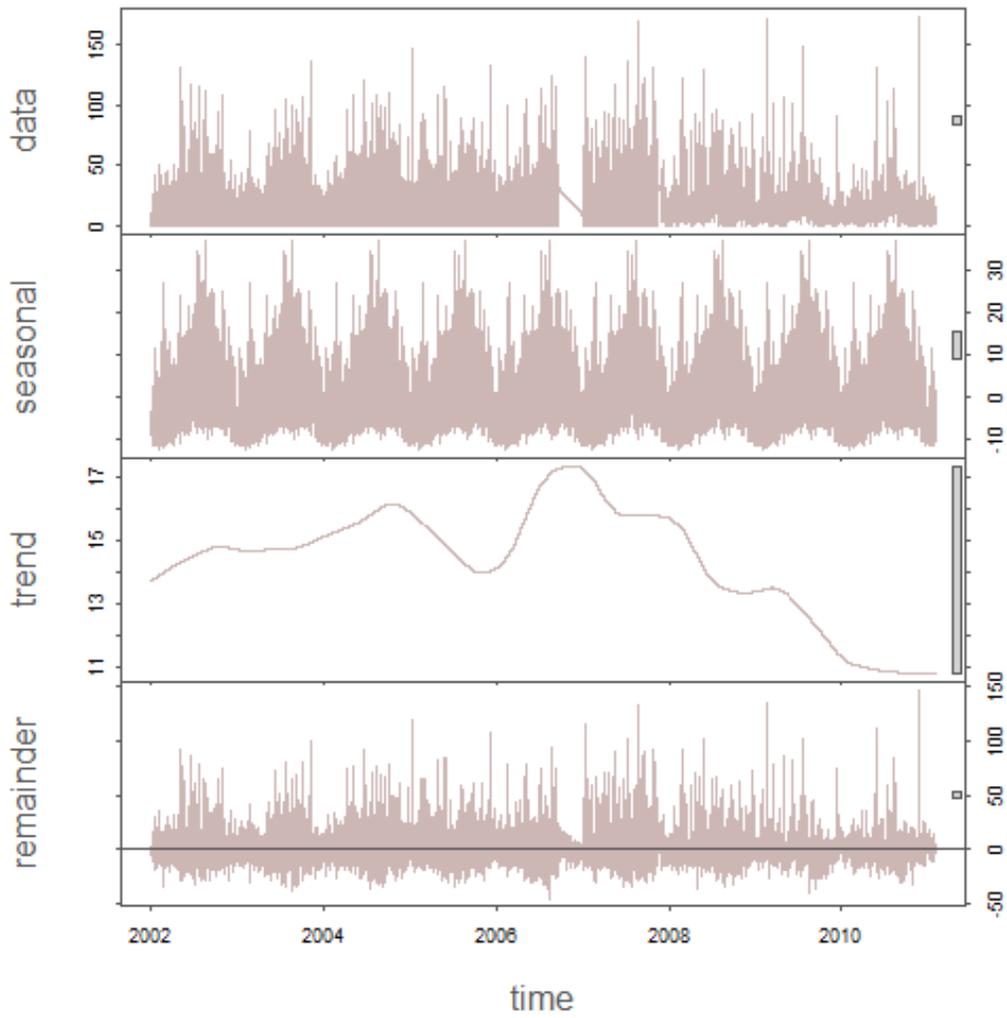
Object E-66 'STL chart for Whistler PM<sub>PM2.5</sub> TEOM 2004 to 2013'

### STL Chart for Langdale PM10



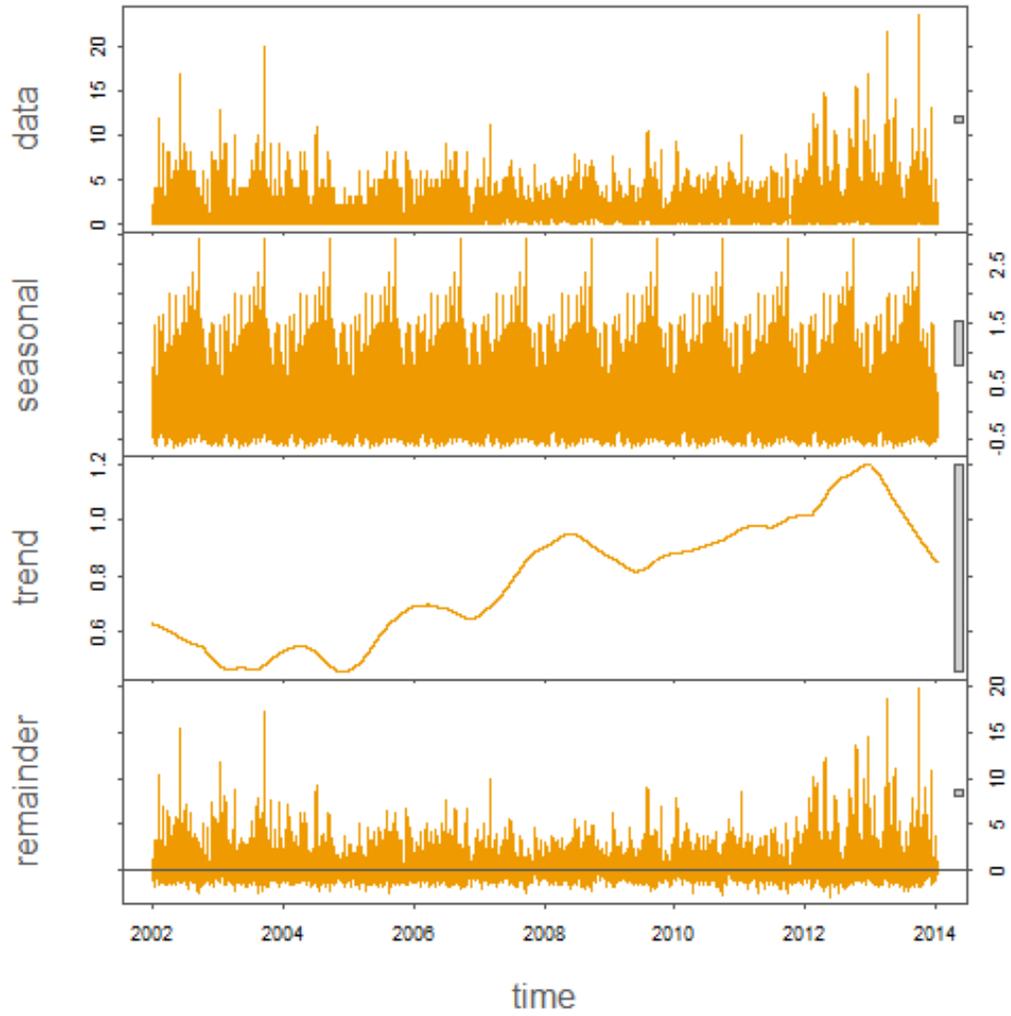
Object E-66 'STL chart for Langdale PM<sub>10</sub>, 2002 to 2013'

### STL Chart for Squamish PM10



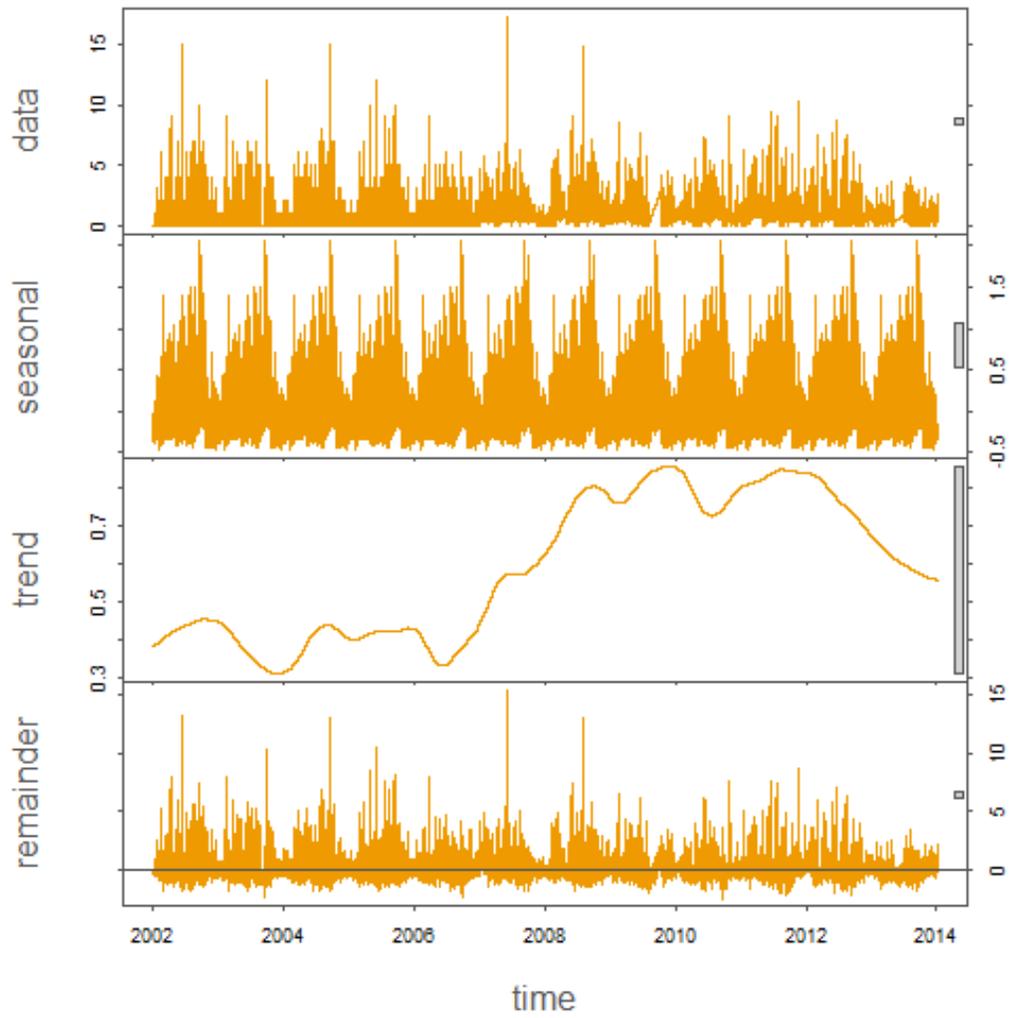
Object E-67 'STL chart for Squamish PM<sub>10</sub> 2002 to 2011'

### STL Chart for Langdale SO<sub>2</sub>



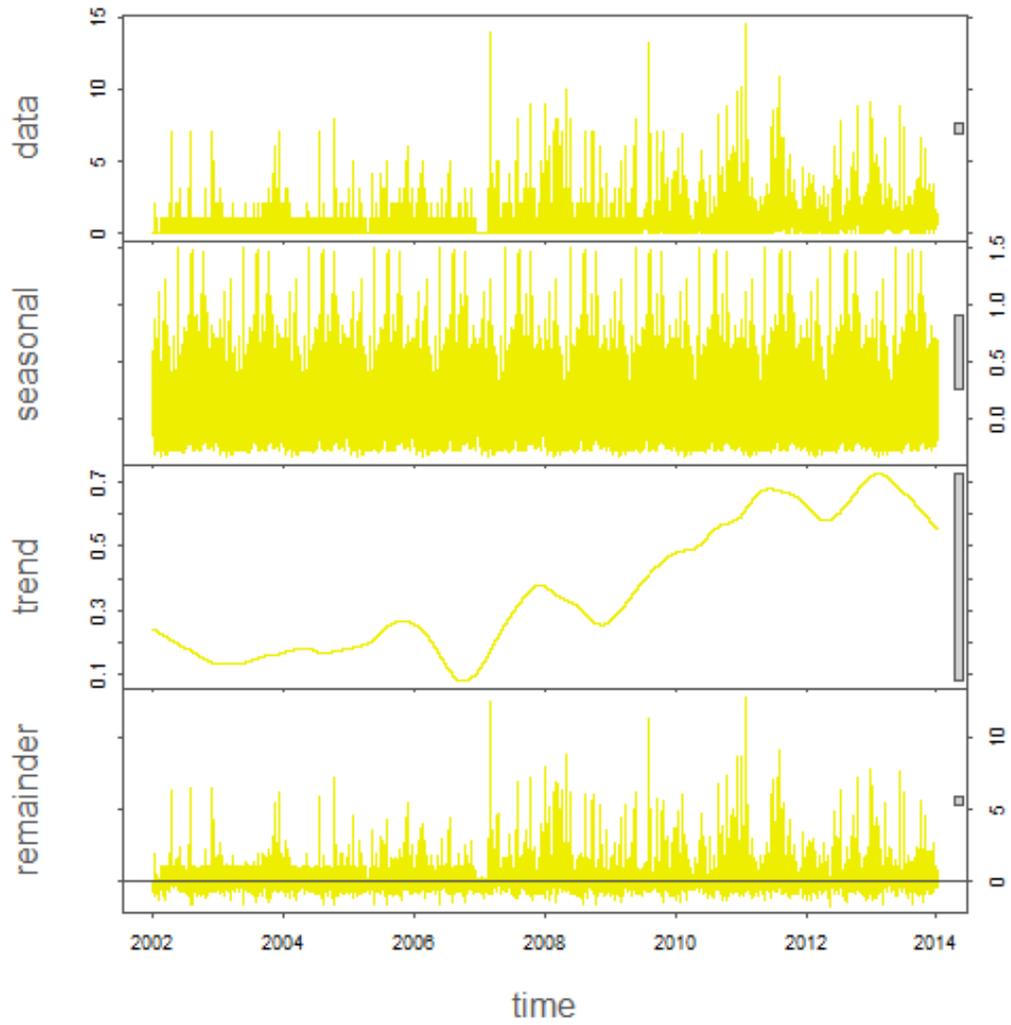
Object E-68 'STL chart for Langdale SO<sub>2</sub>, 2002 to 2013'

### STL Chart for Squamish SO2



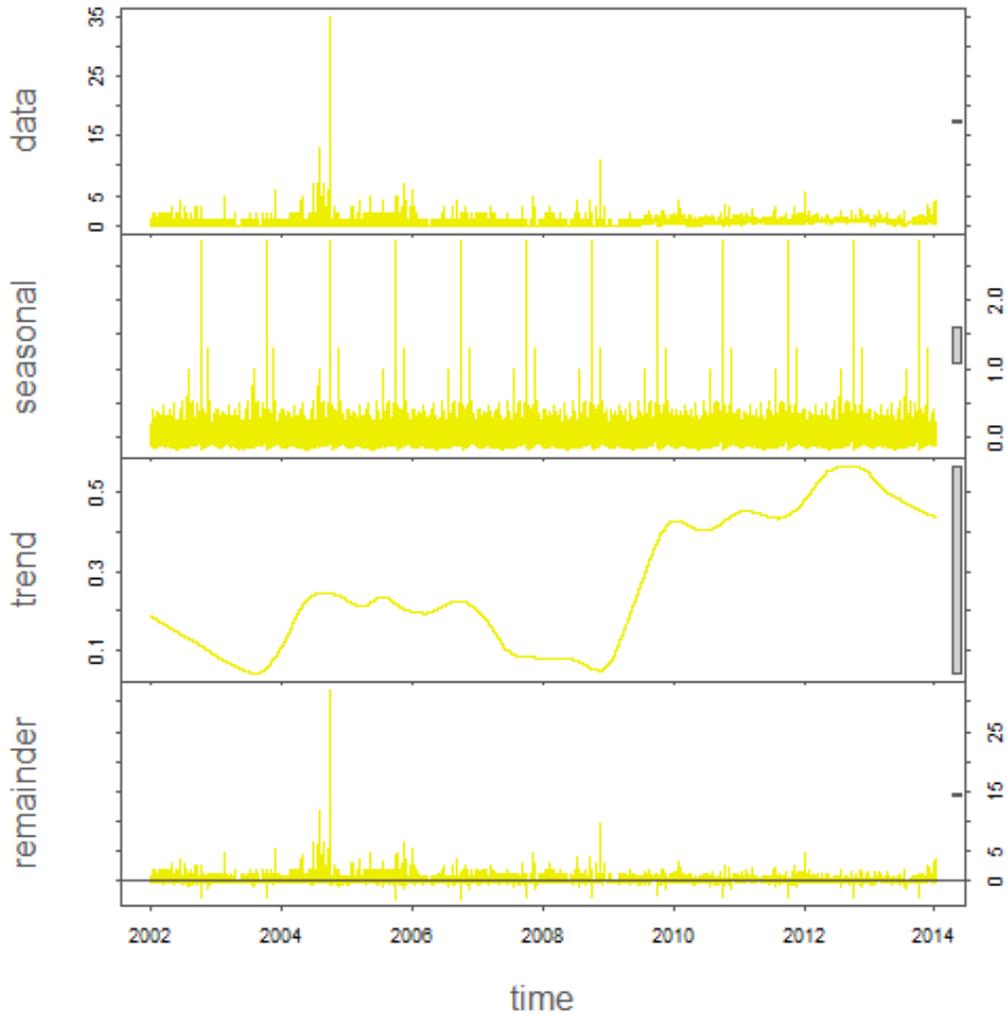
Object E-69 'STL chart for Squamish SO<sub>2</sub>, 2002 to 2013'

### STL Chart for Langdale TRS



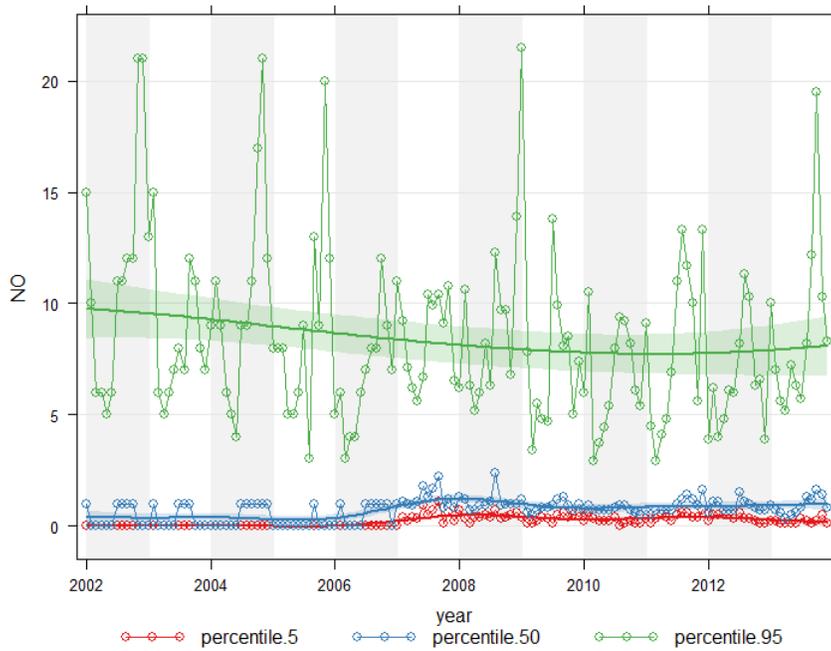
Object E-70 'STL chart for Langdale TRS, 2002 to 2013'

### STL Chart for Squamish TRS



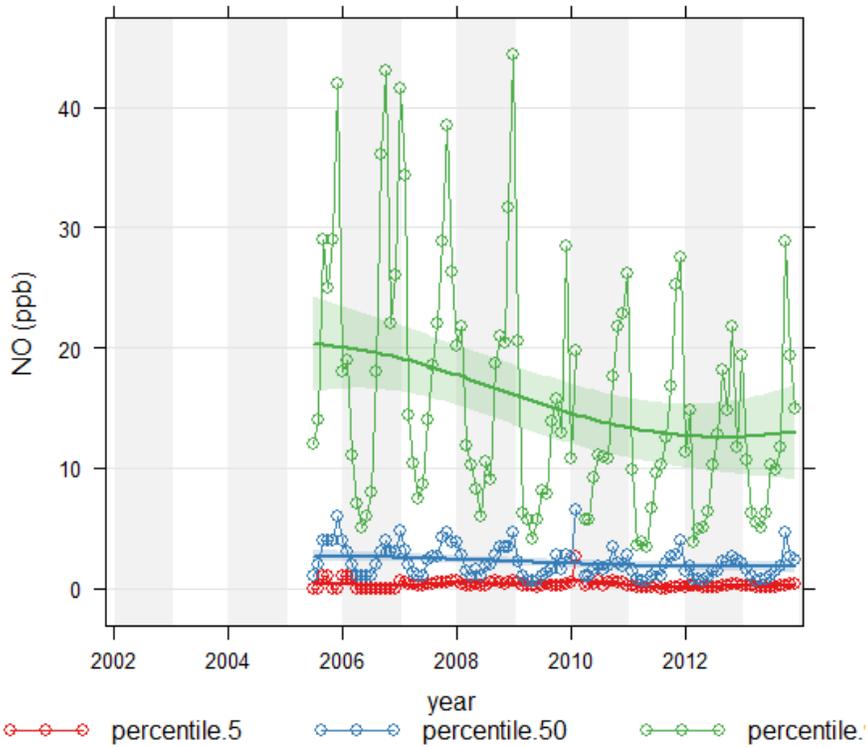
Object E-71 'STL chart for Whistler TRS, 2002 to 2013'

Percentile Plot for Langdale NO

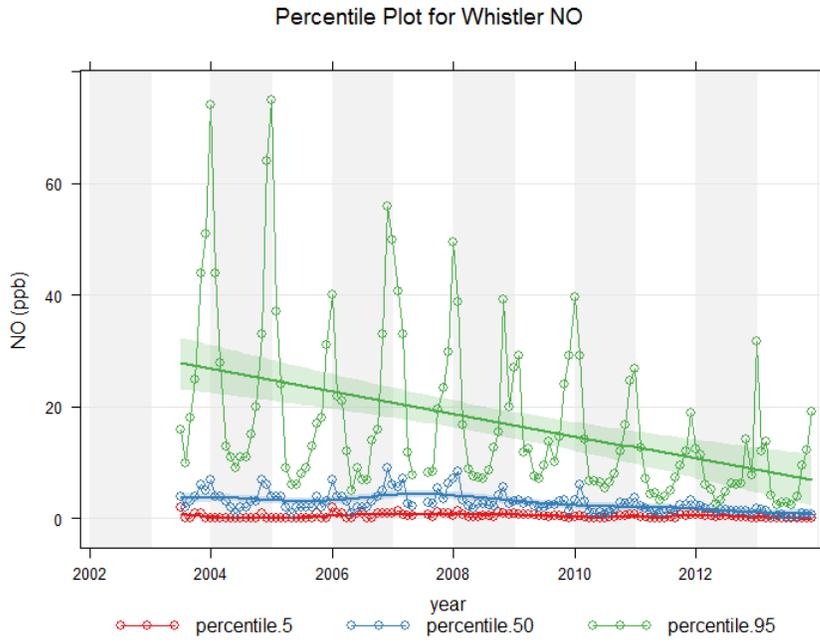


Object E-72 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Langdale NO'

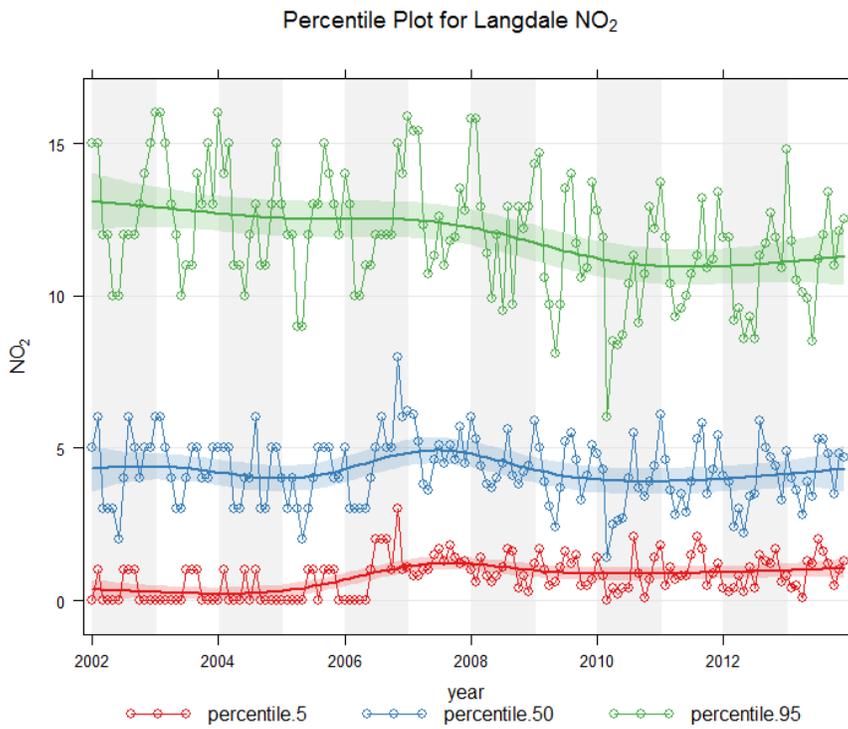
Percentile Plot for Squamish NO



Object E-73 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish NO'

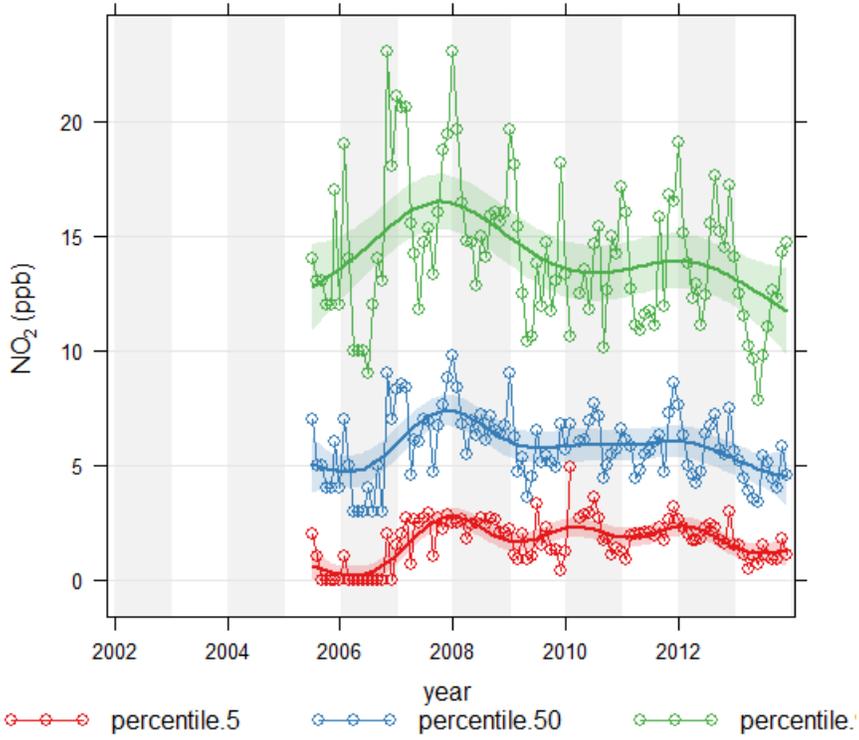


Object E-74 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Whistler NO'



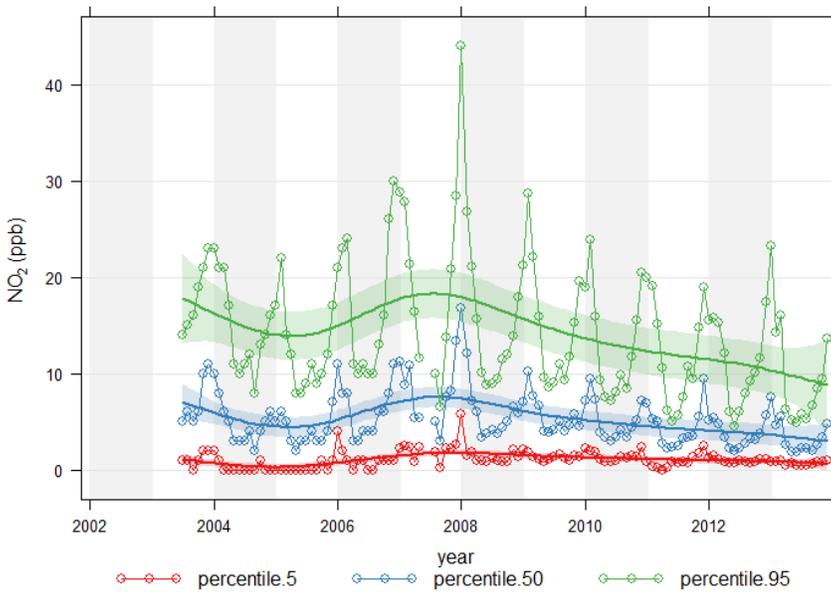
Object E-75 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Langdale NO<sub>2</sub>'

### Percentile Plot for Squamish NO<sub>2</sub>



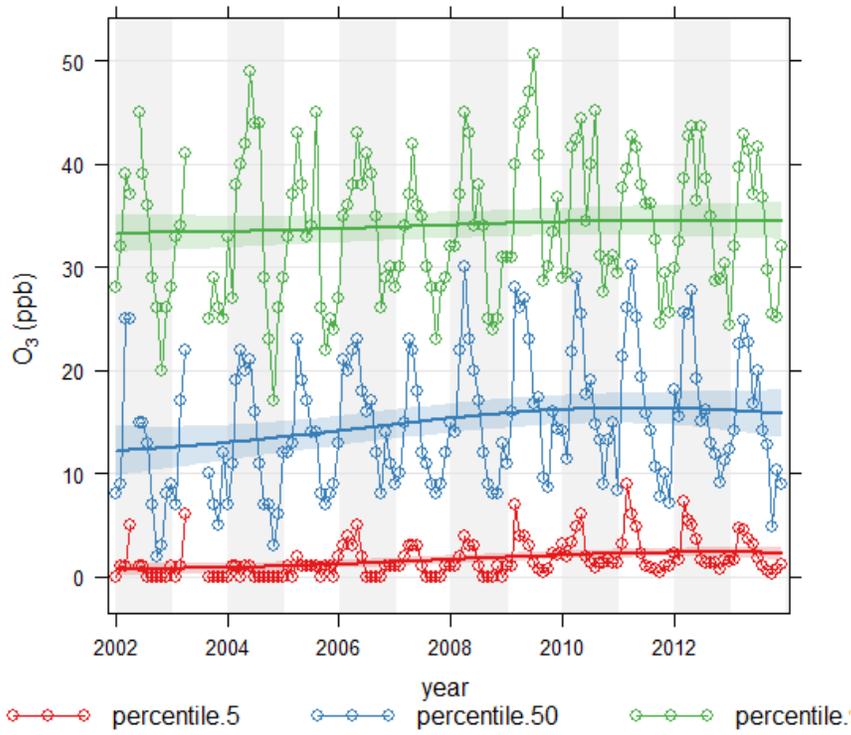
Object E-76 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish NO<sub>2</sub>'

### Percentile Plot for Whistler NO<sub>2</sub>



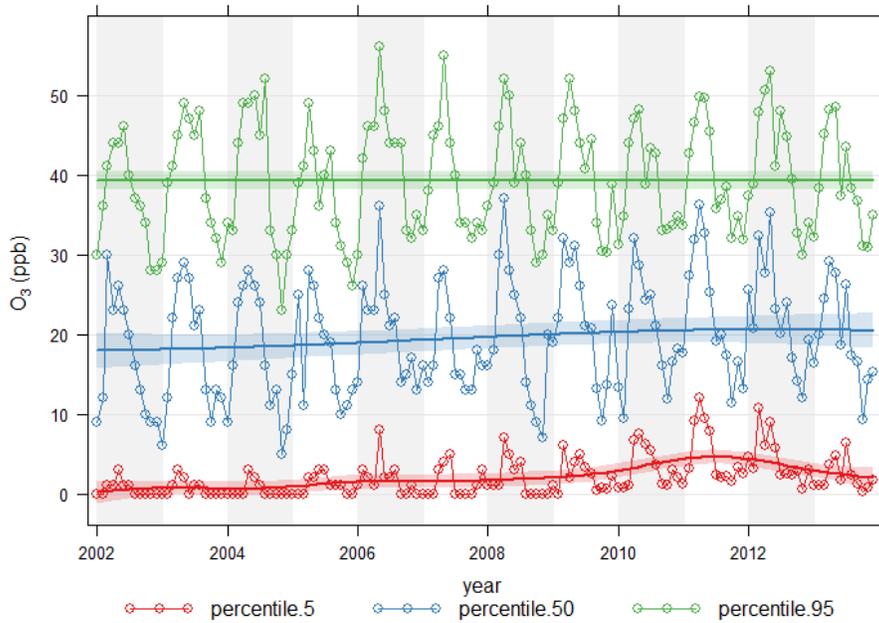
Object E-77 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Whistler NO<sub>2</sub>'

### Percentile Plot for Squamish O<sub>3</sub>



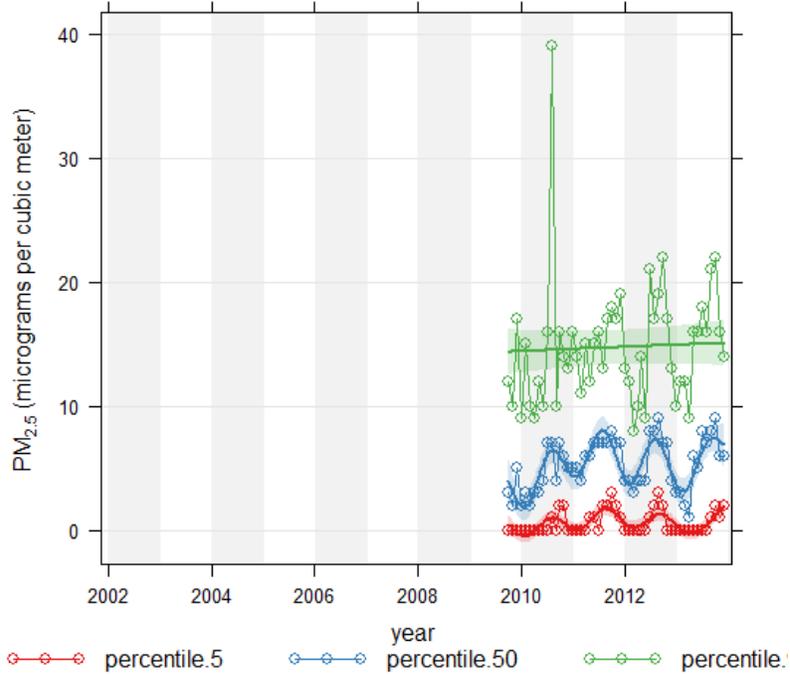
Object E-78 Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish O<sub>3</sub>

### Percentile Plot for Whistler O<sub>3</sub>



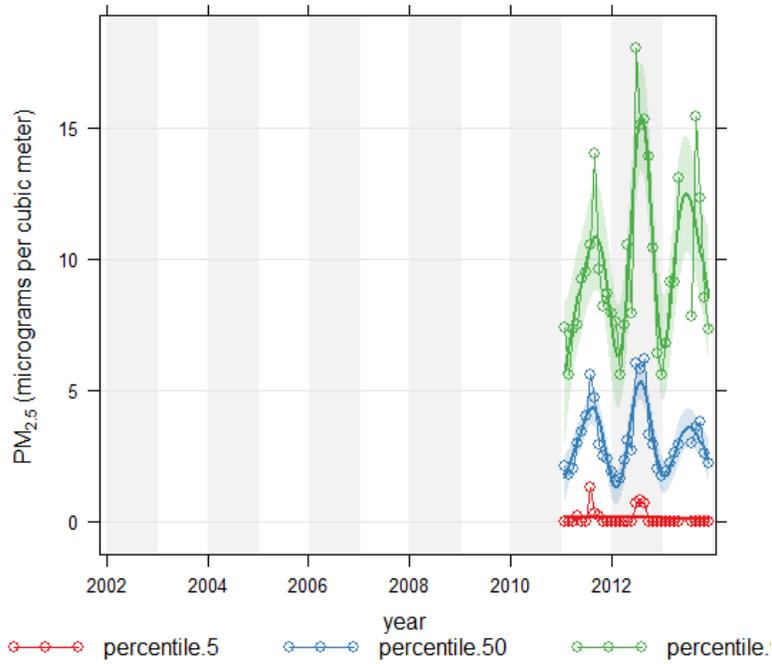
Object E-79 Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Whistler O<sub>3</sub>

### Percentile Plot for Squamish PM<sub>2.5</sub>

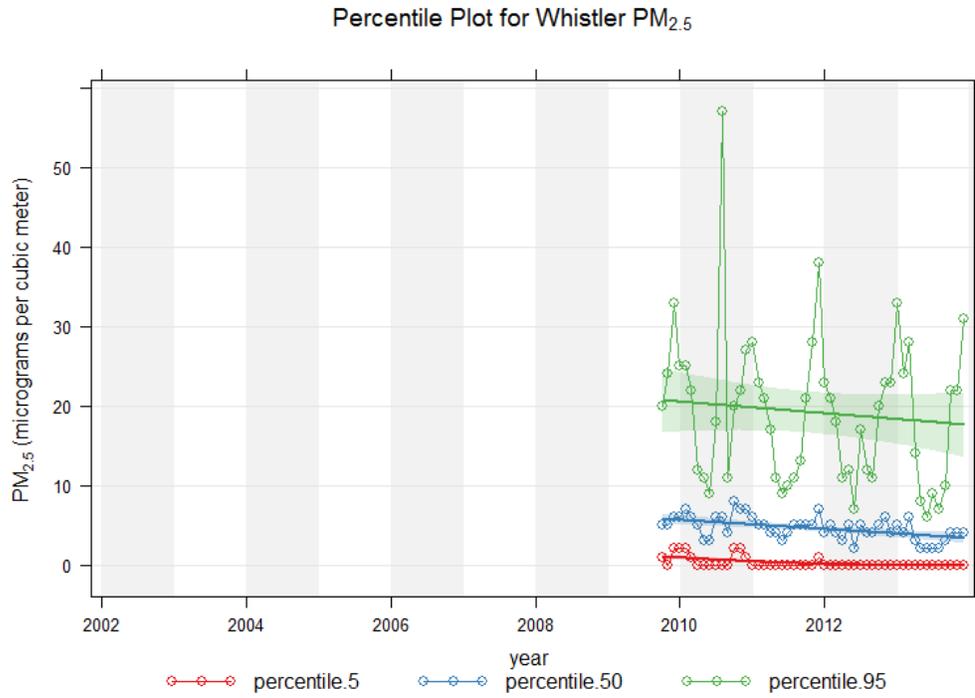


Object E-80 Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish PM<sub>2.5</sub> BAM

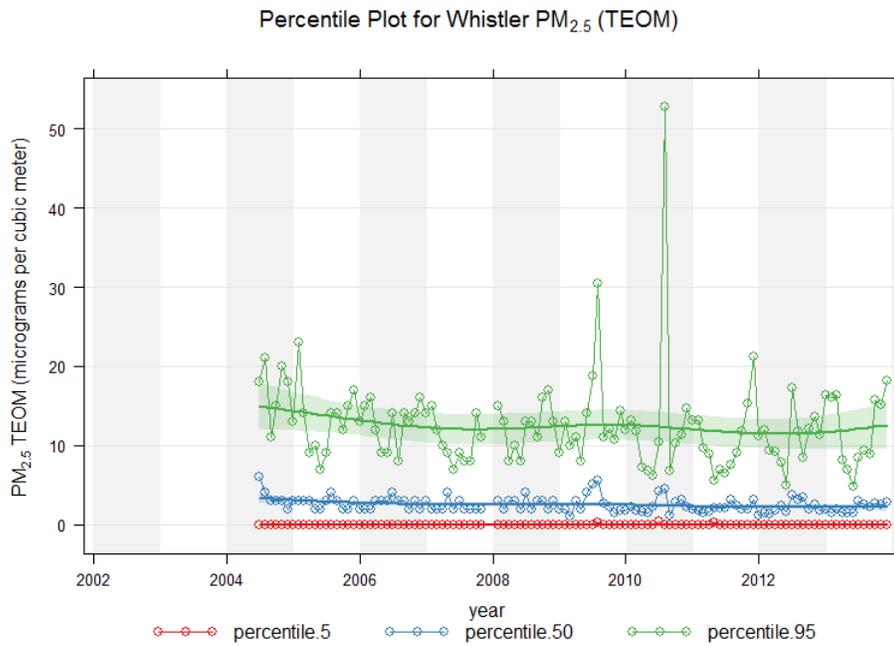
### Percentile Plot for Squamish PM<sub>2.5</sub> (TEOM)



Object E-81 Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish PM<sub>2.5</sub> TEOM

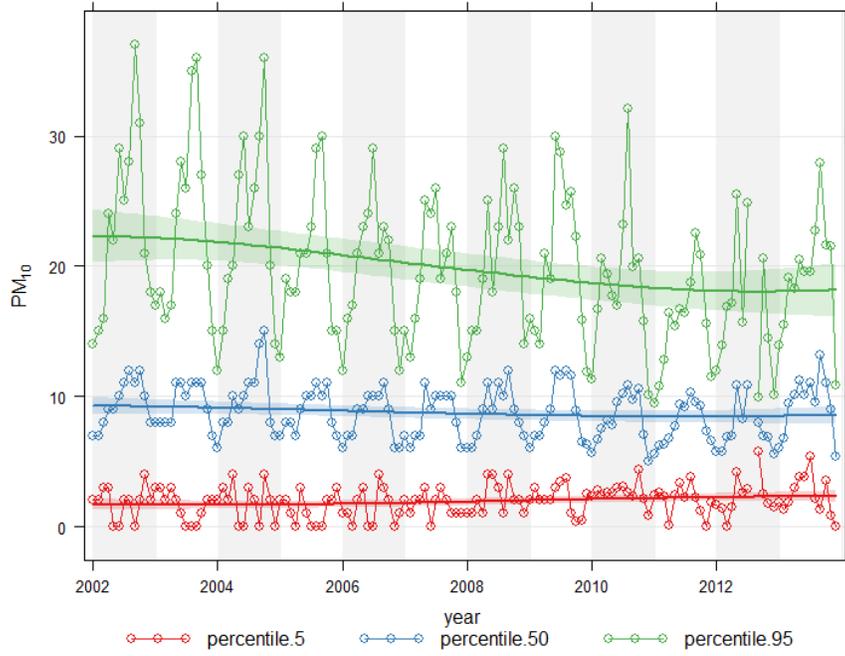


Object E-82 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Whistler PM<sub>2.5</sub> BAM'



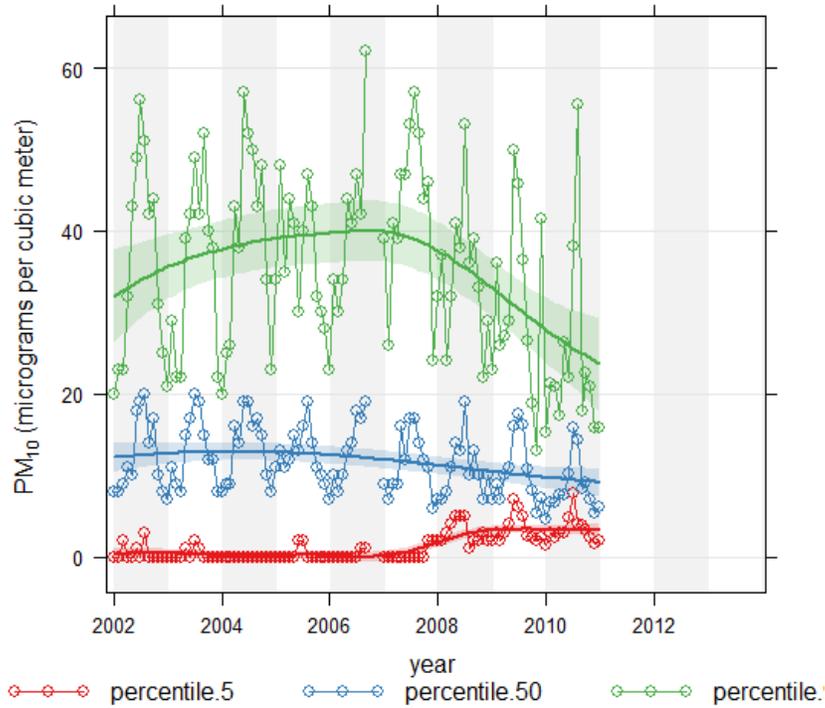
Object E-83 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Whistler PM<sub>2.5</sub> TEOM'

Percentile Plot for Langdale PM<sub>10</sub>



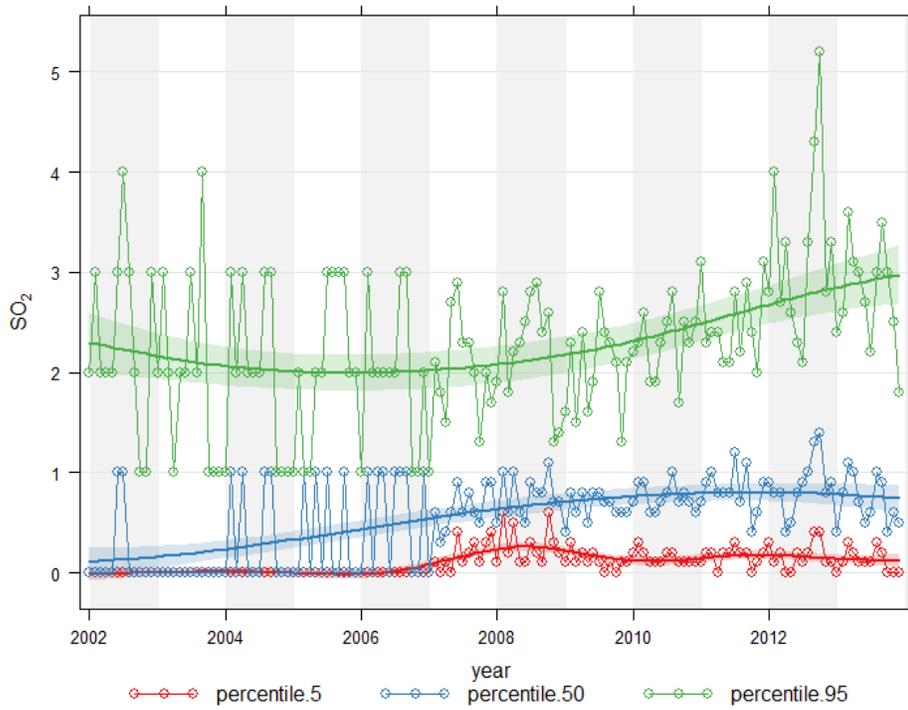
Object E-84 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Langdale PM<sub>10</sub>'

Percentile Plot for Squamish PM<sub>10</sub>



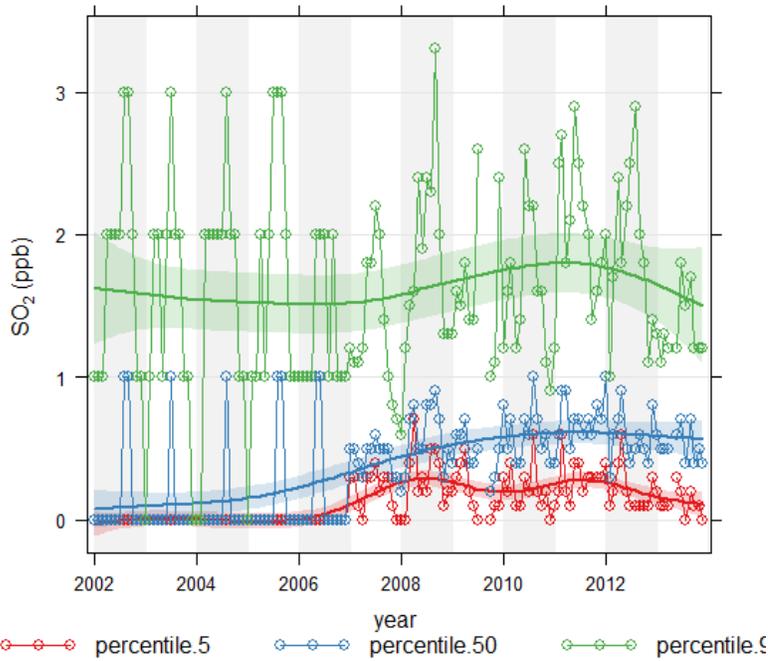
Object E-85 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish PM<sub>10</sub>'

### Percentile Plot for Langdale SO<sub>2</sub>



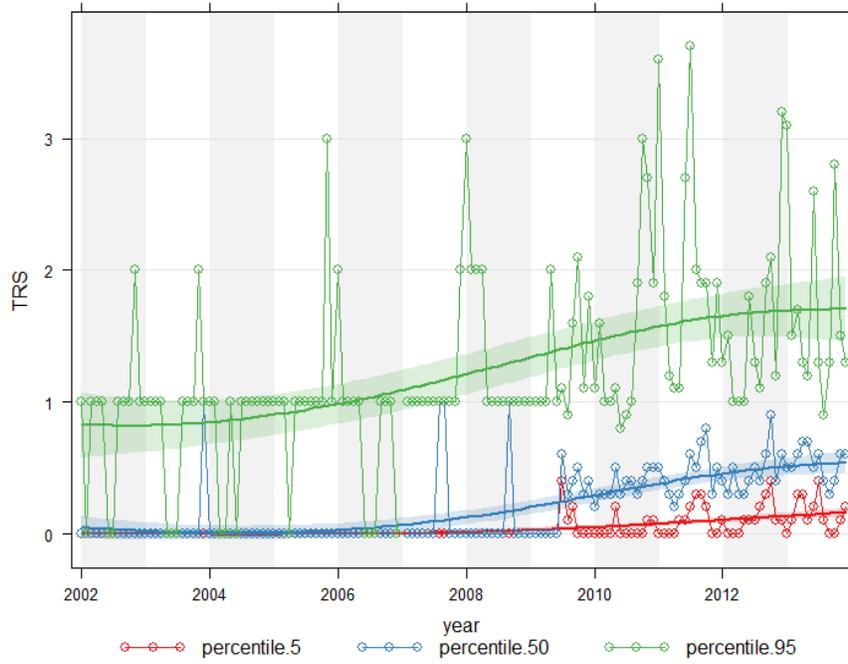
Object E-86 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Langdale SO<sub>2</sub>'

### Percentile Plot for Squamish SO<sub>2</sub>



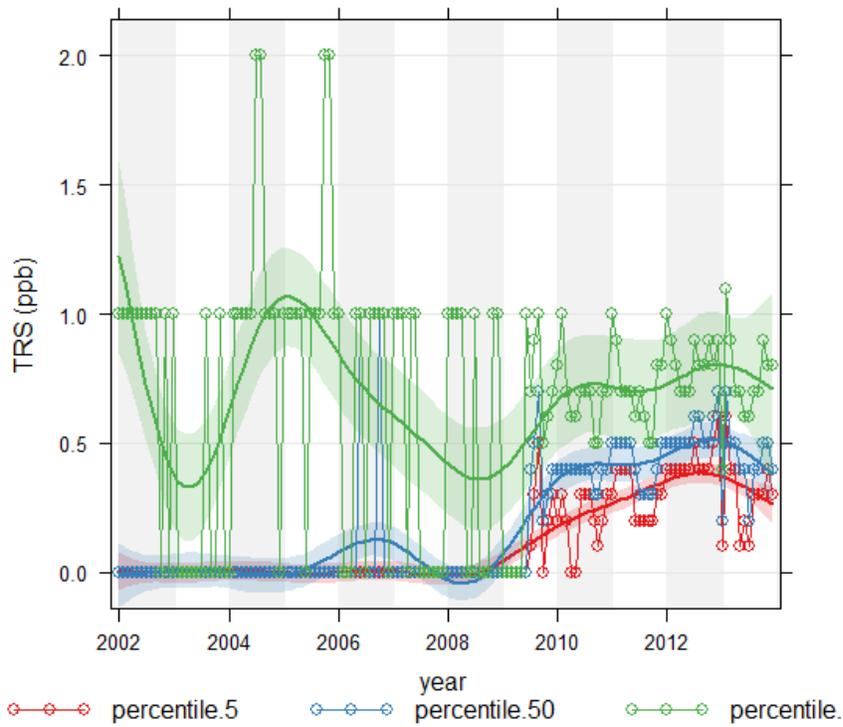
Object E-87 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish SO<sub>2</sub>'

Percentile Plot for Langdale TRS



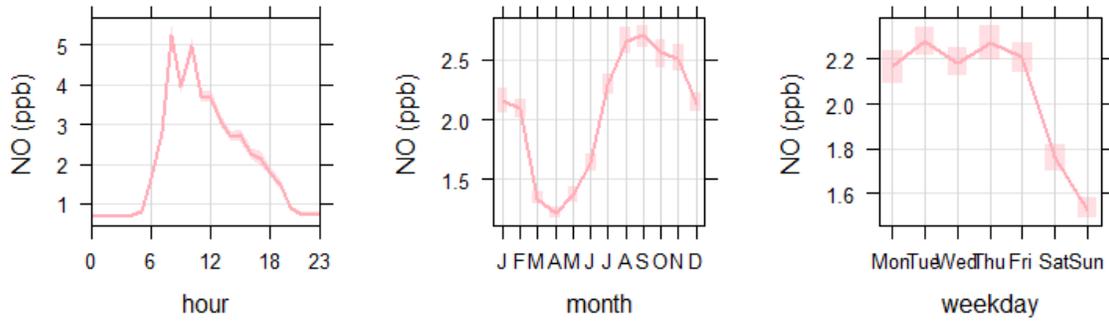
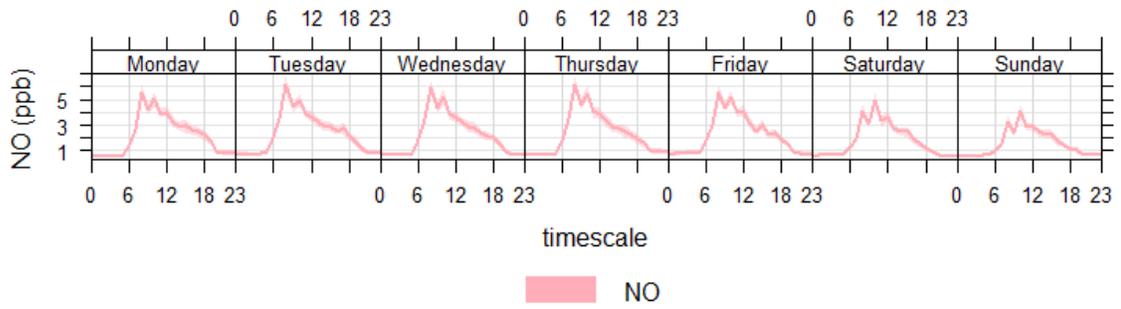
Object E-88 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Langdale TRS'

Percentile Plot for Squamish TRS



Object E-89 'Plot of 95<sup>th</sup>, 50<sup>th</sup> and 5<sup>th</sup> percentiles for Squamish TRS'

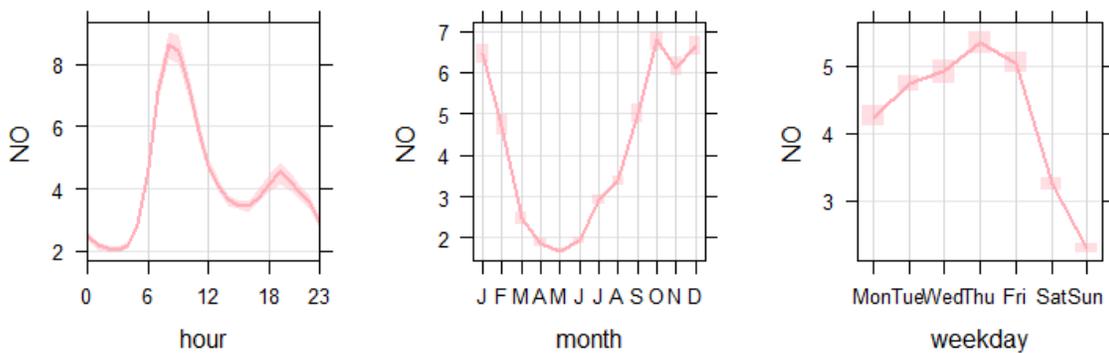
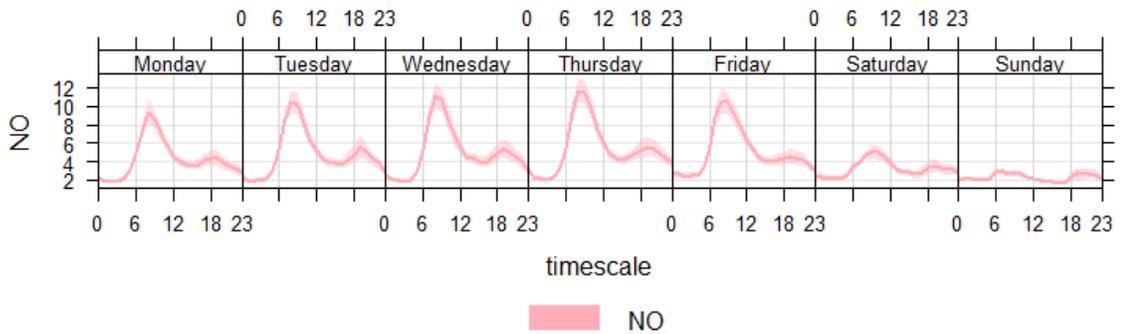
### Time Variation Plot for Langdale NO, All Available Data



mean and 95% confidence interval in mean

Object E-90 'Time variation plots showing diurnal, weekly and monthly patterns for Langdale NO'

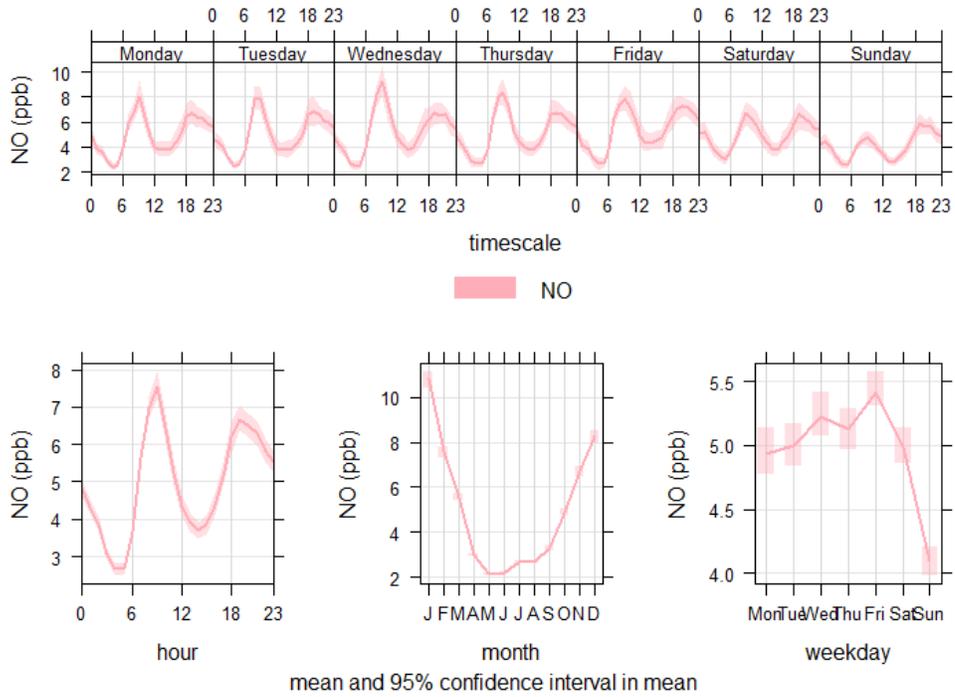
### Time Variation Plot for Squamish NO, All Available Data



mean and 95% confidence interval in mean

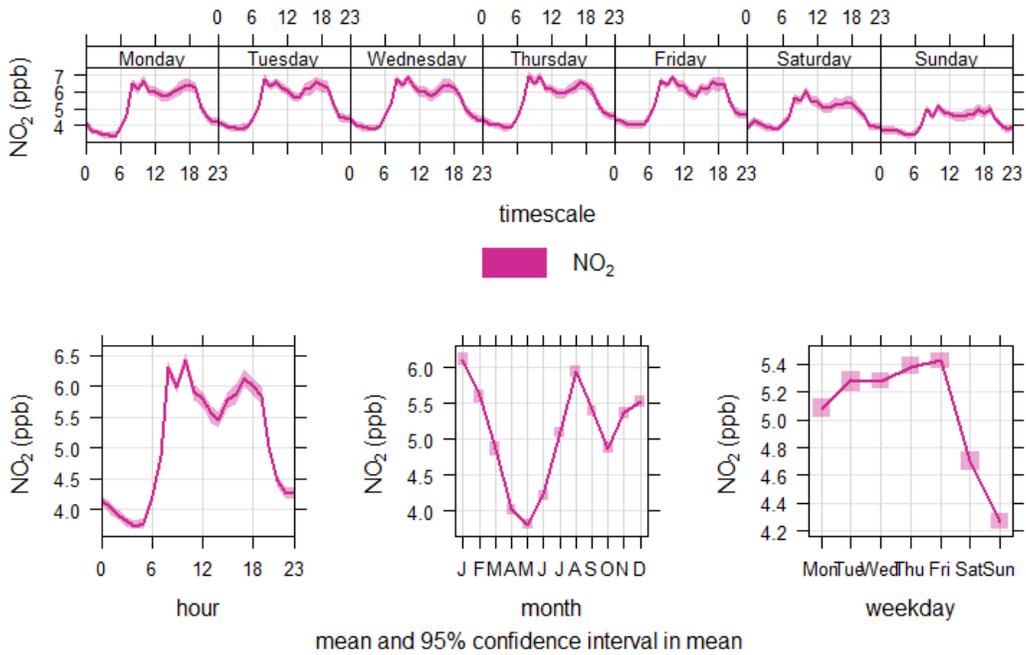
Object E-91 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish NO'

Time Variation Plot for Whistler NO, All Available Data



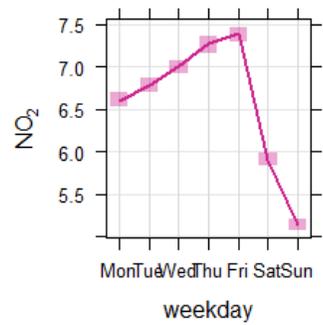
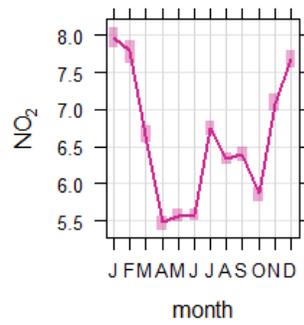
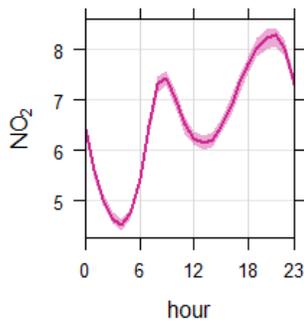
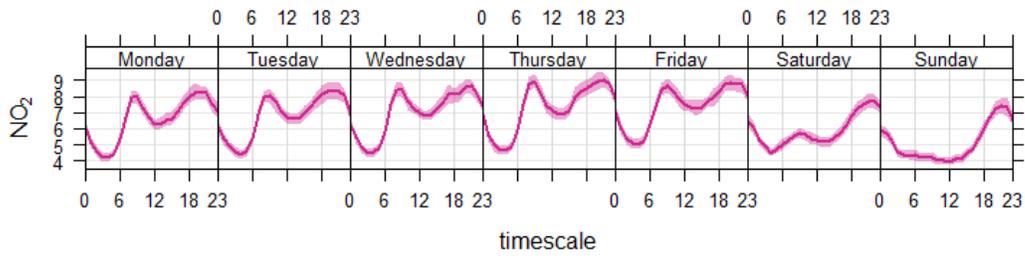
Object E-92 Time variation plots showing diurnal, weekly and monthly patterns for Whistler NO'

Time Variation Plot for Langdale NO<sub>2</sub>, All Available Data



Object E-93 Time variation plots showing diurnal, weekly and monthly patterns for Langdale NO<sub>2</sub>'

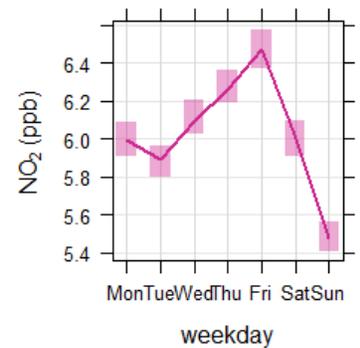
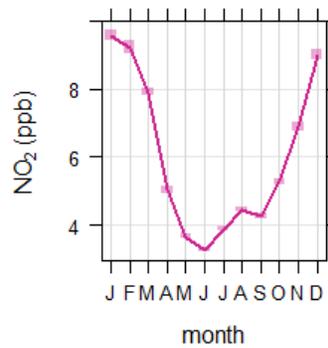
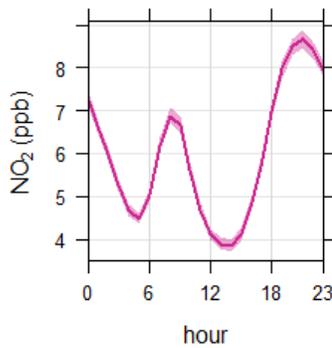
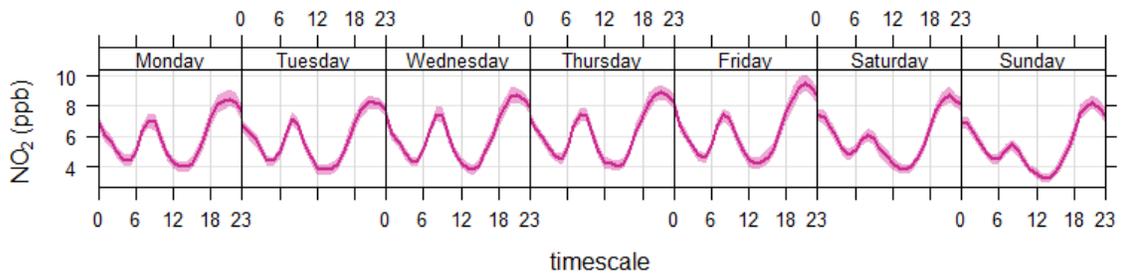
### Time Variation Plot for Squamish NO<sub>2</sub>, All Available Data



mean and 95% confidence interval in mean

Object E-94 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish NO<sub>2</sub>'

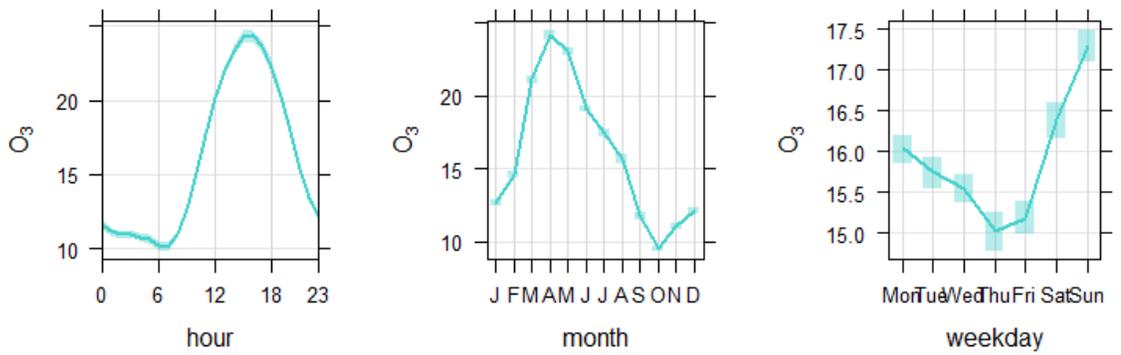
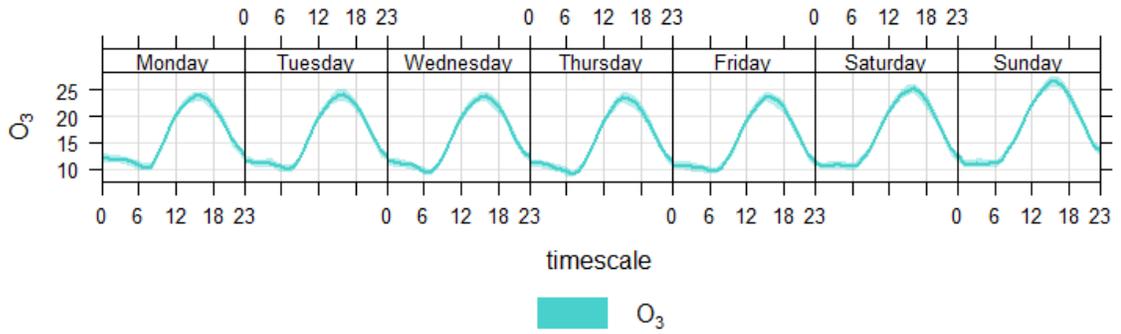
### Time Variation Plot for Whistler NO<sub>2</sub>, All Available Data



mean and 95% confidence interval in mean

Object E-95 'Time variation plots showing diurnal, weekly and monthly patterns for Whistler NO<sub>2</sub>'

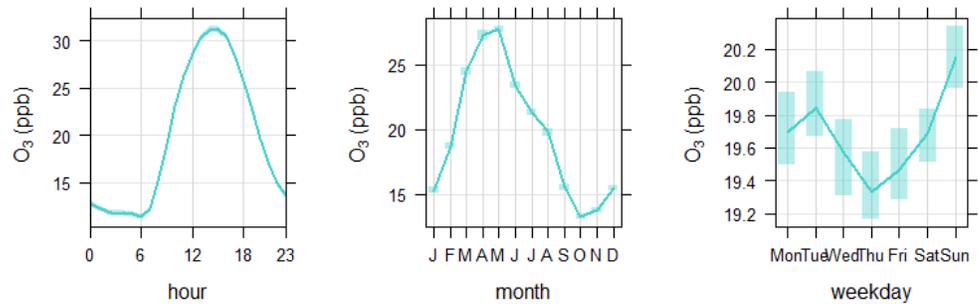
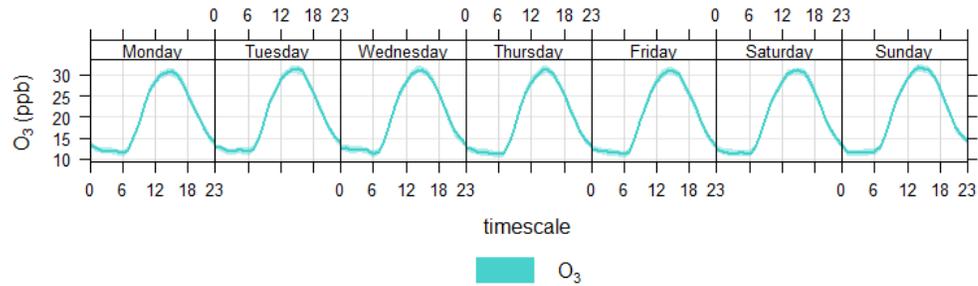
### Time Variation Plot for Squamish O<sub>3</sub>, All Available Data



mean and 95% confidence interval in mean

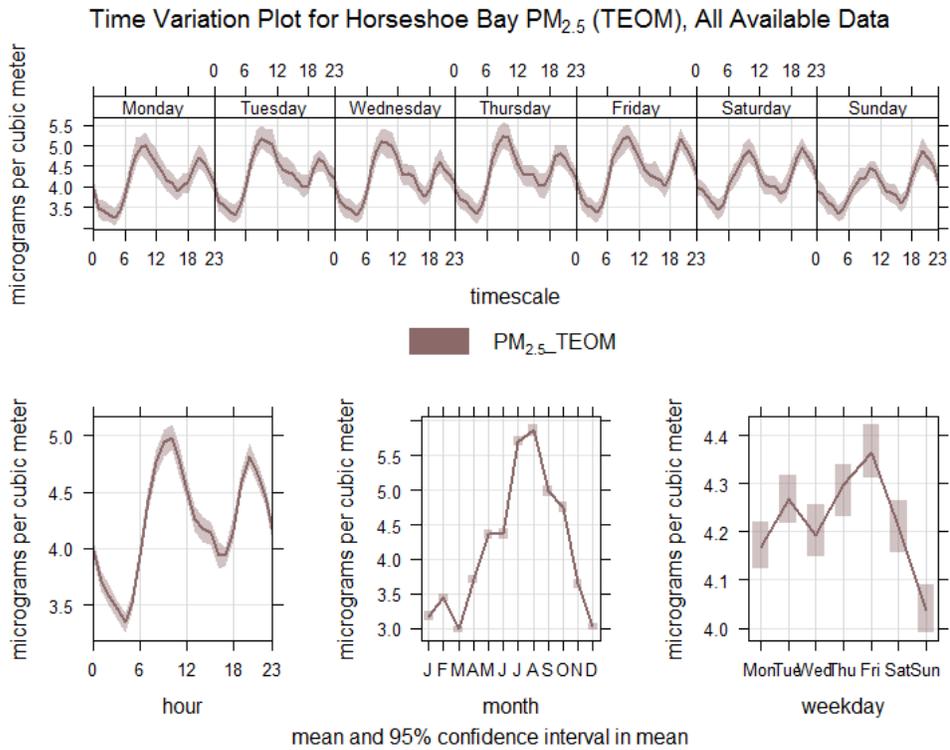
Object E-96 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish O<sub>3</sub>'

### Time Variation Plot for Whistler O<sub>3</sub>, All Available Data

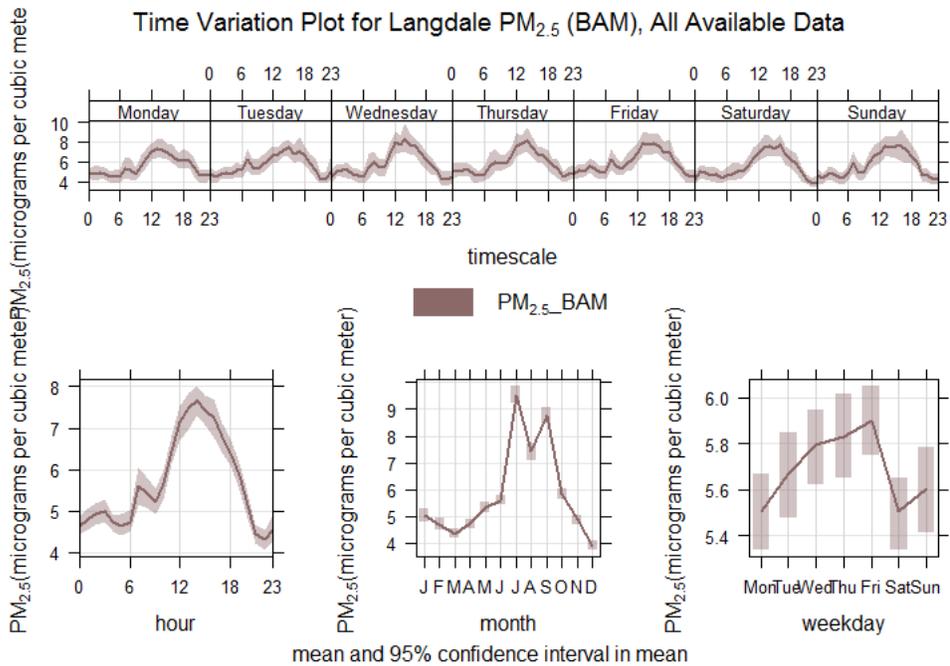


mean and 95% confidence interval in mean

Object E-97 'Time variation plots showing diurnal, weekly and monthly patterns for Whistler O<sub>3</sub>'

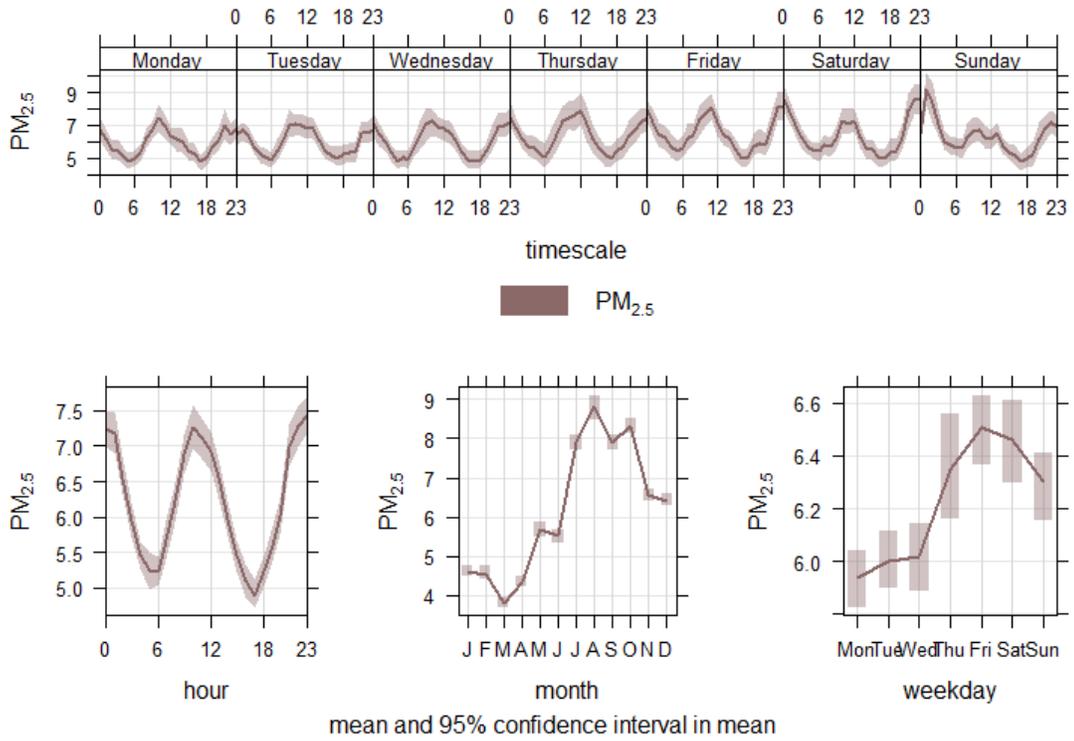


Object E-99 'Time variation plots showing diurnal, weekly and monthly patterns for Horseshoe Bay PM<sub>2.5</sub> TEOM'



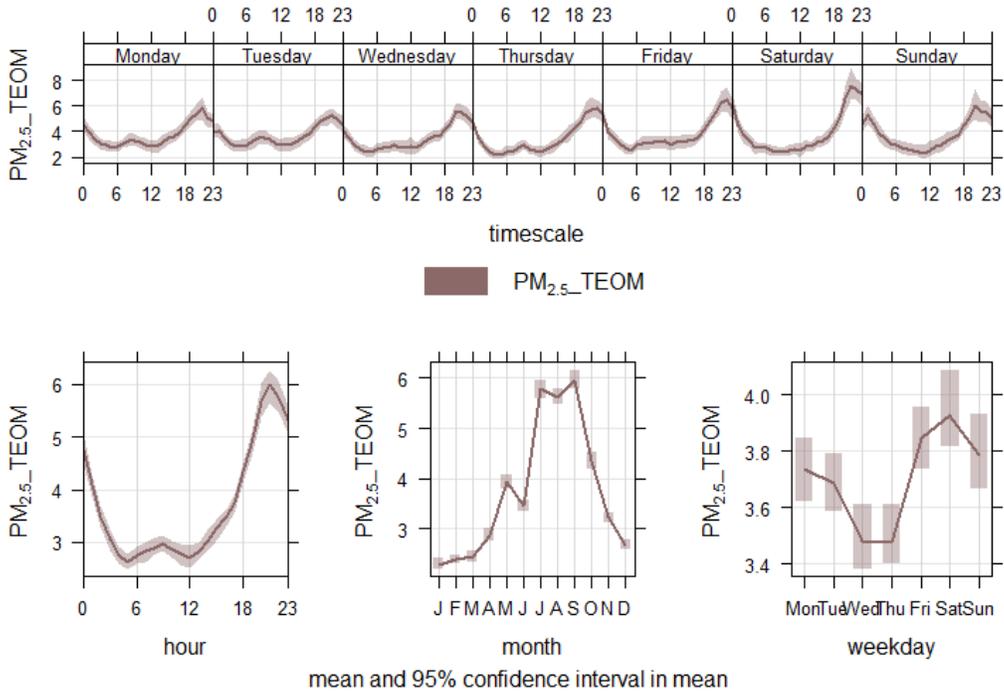
Object E-100 'Time variation plots showing diurnal, weekly and monthly patterns for Langdale PM<sub>2.5</sub> BAM'

### Time Variation Plot for Squamish PM<sub>2.5</sub>, All Available Data

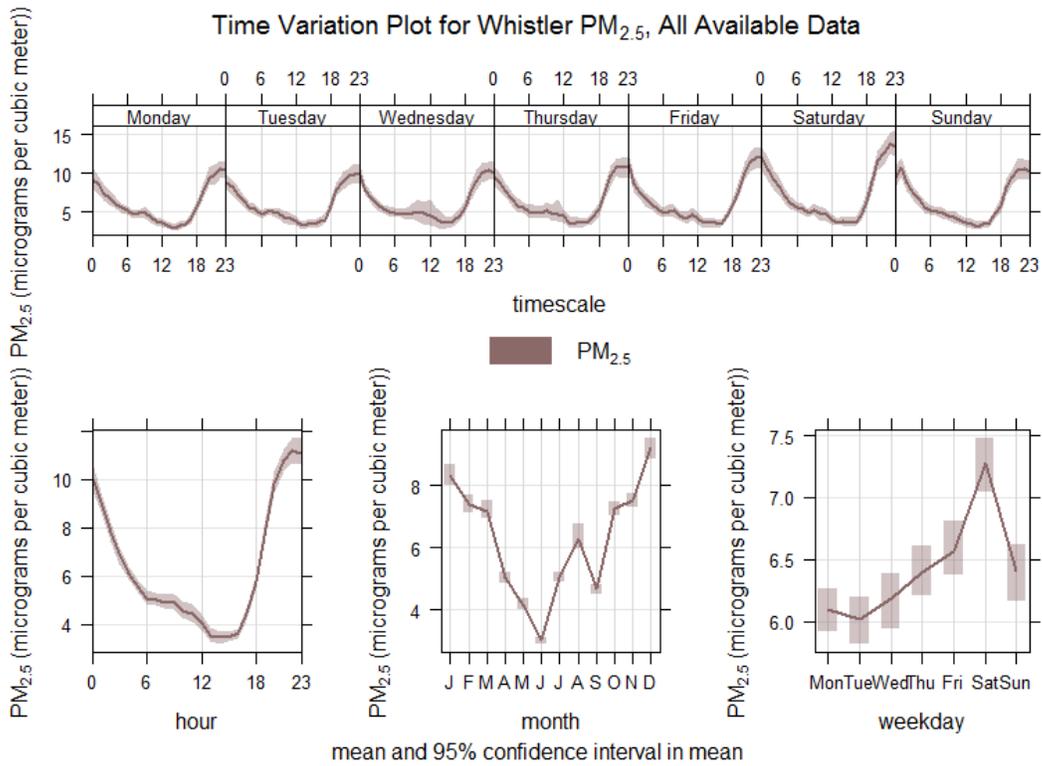


Object E-101 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish PM<sub>2.5</sub> BAM'

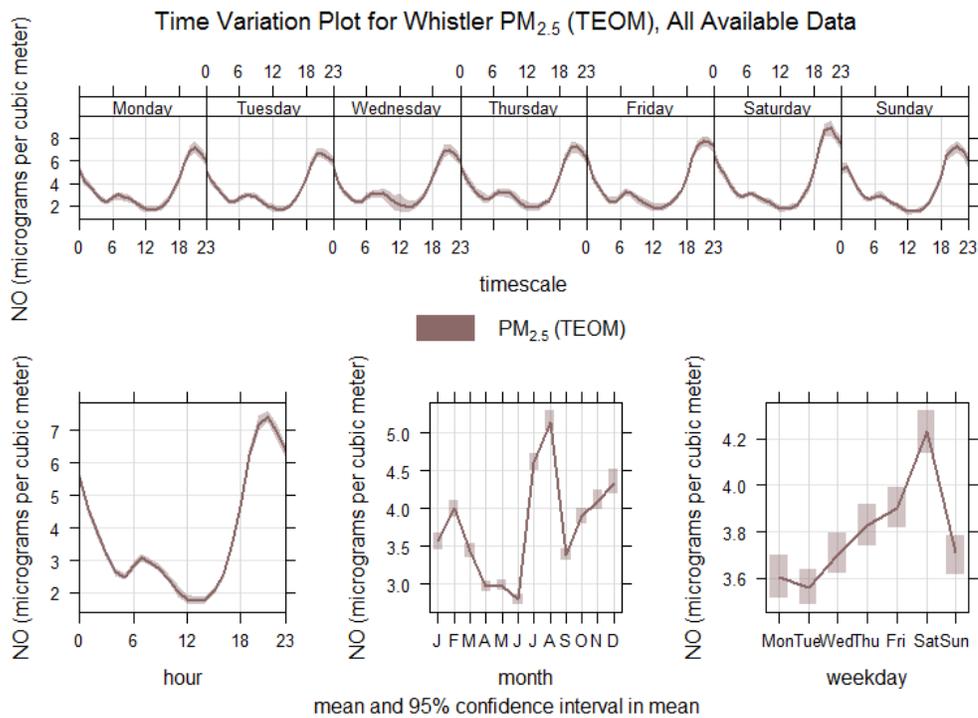
### Time Variation Plot for Squamish PM<sub>2.5</sub> (TEOM), All Available Data



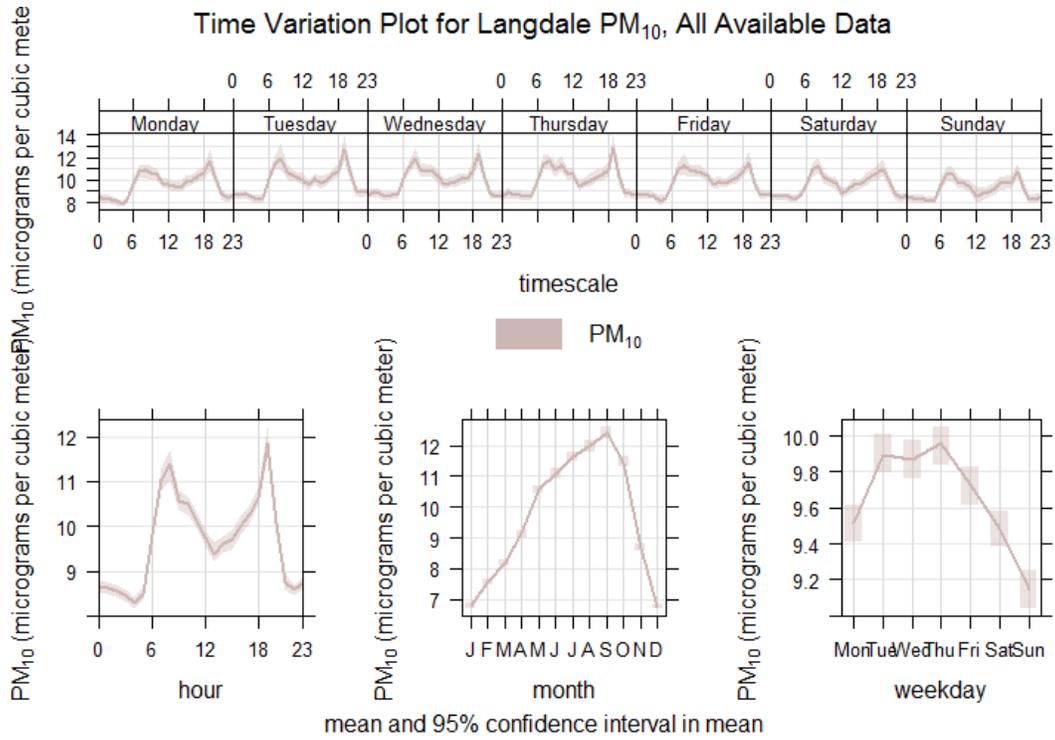
Object E-102 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish PM<sub>2.5</sub> TEOM'



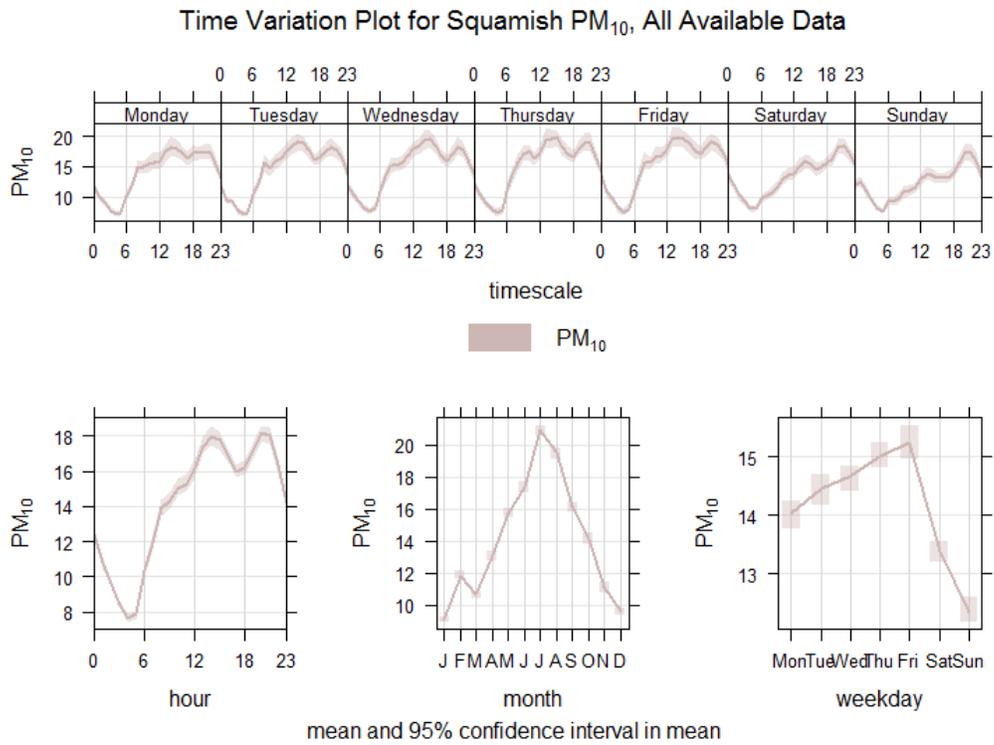
Object E-103 'Time variation plots showing diurnal, weekly and monthly patterns for Whistler PM<sub>2.5</sub>, BAM'



Object E-104 'Time variation plots showing diurnal, weekly and monthly patterns for Whistler PM<sub>2.5</sub>, TEOM'

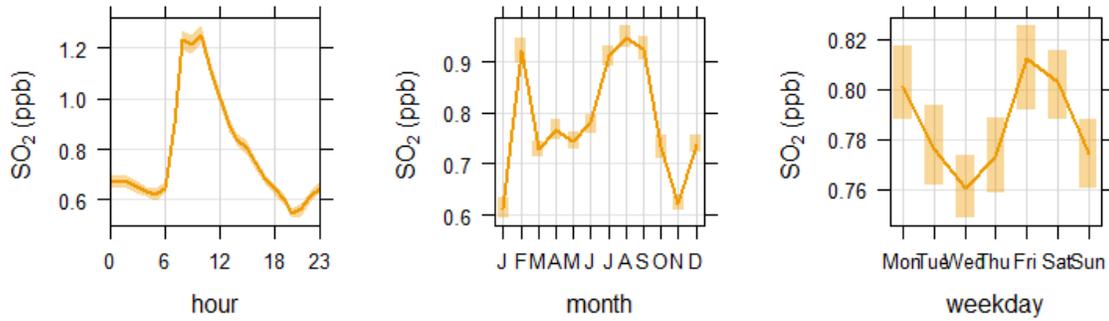
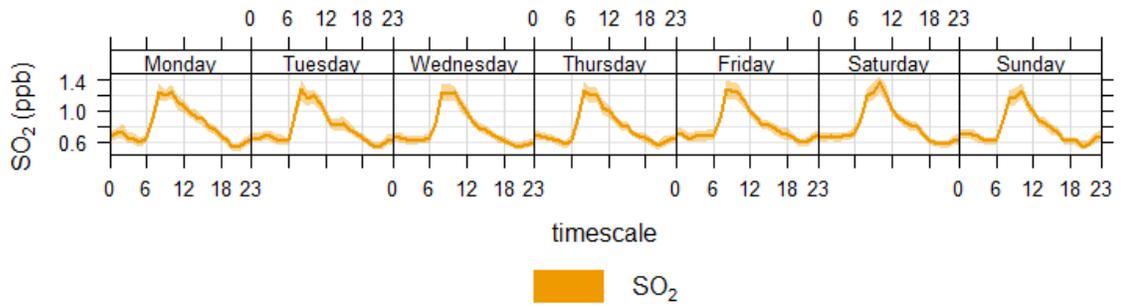


Object E-105 'Time variation plots showing diurnal, weekly and monthly patterns for Langdale PM<sub>10</sub>'



Object E-106 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish PM<sub>10</sub>'

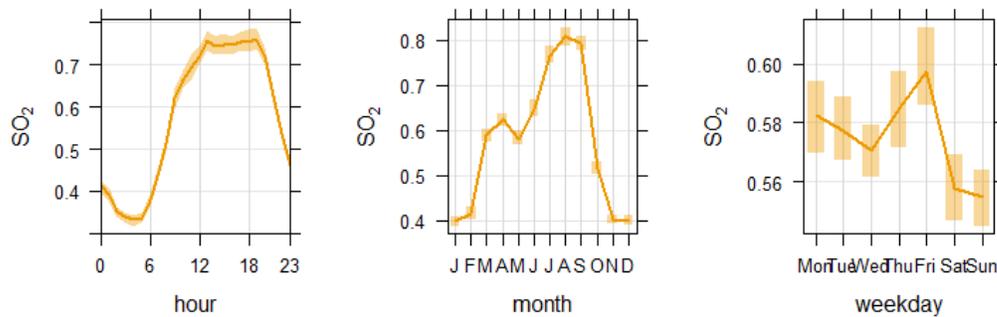
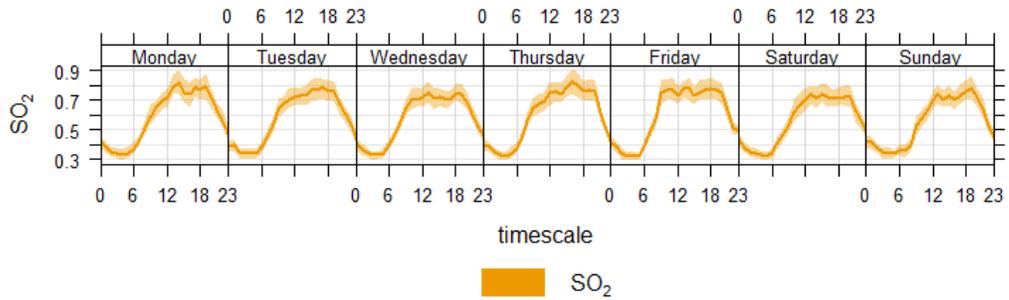
### Time Variation Plot for Langdale SO<sub>2</sub>, All Available Data



mean and 95% confidence interval in mean

Object E-107 'Time variation plots showing diurnal, weekly and monthly patterns for Langdale SO<sub>2</sub>'

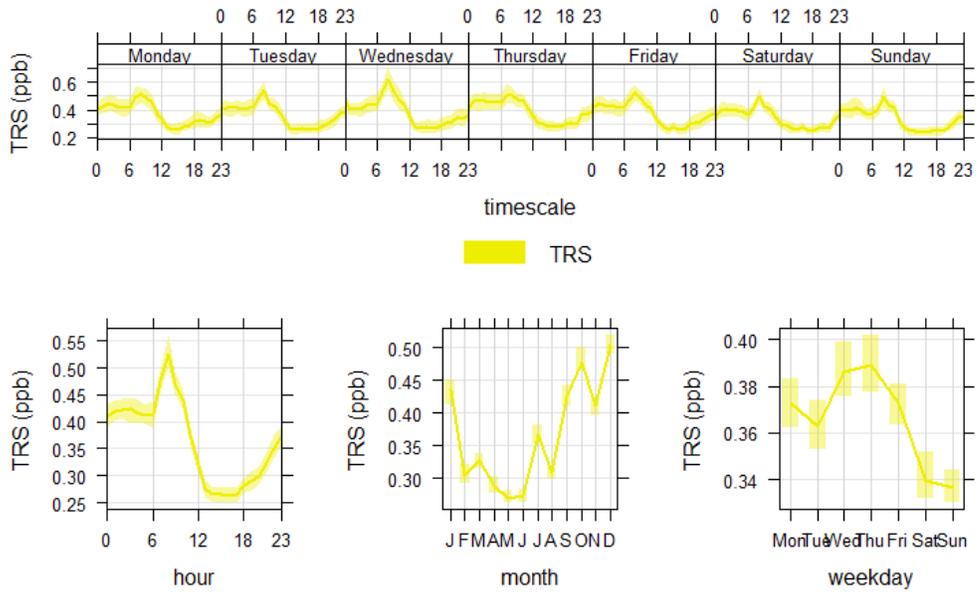
### Time Variation Plot for Squamish SO<sub>2</sub>, All Available Data



mean and 95% confidence interval in mean

Object E-108 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish SO<sub>2</sub>'

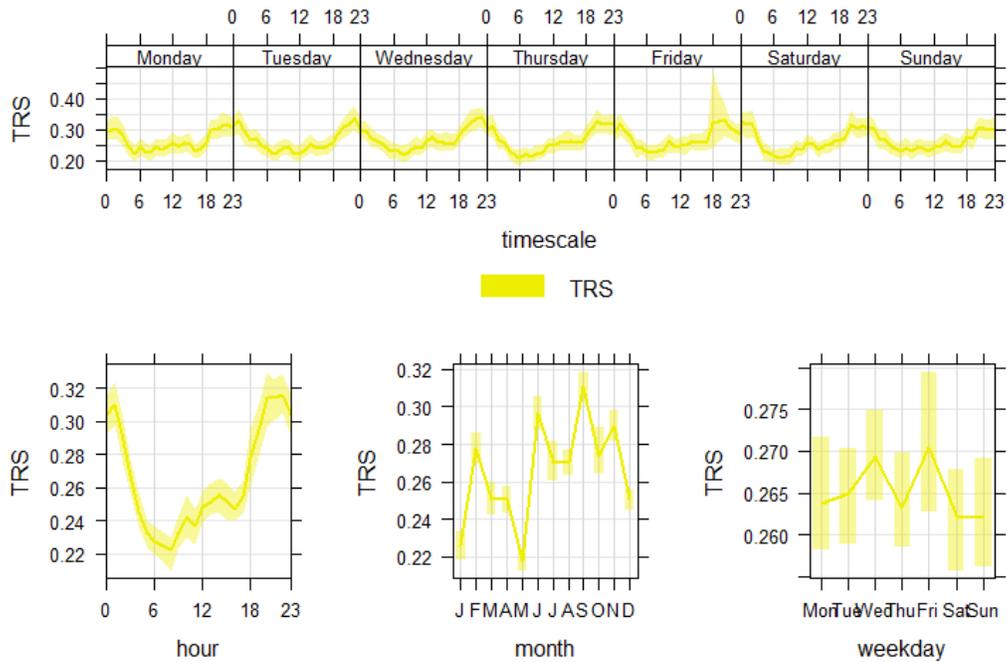
**Time Variation Plot for Langdale TRS, All Available Data**



mean and 95% confidence interval in mean

Object E-109 'Time variation plots showing diurnal, weekly and monthly patterns for Langdale TRS'

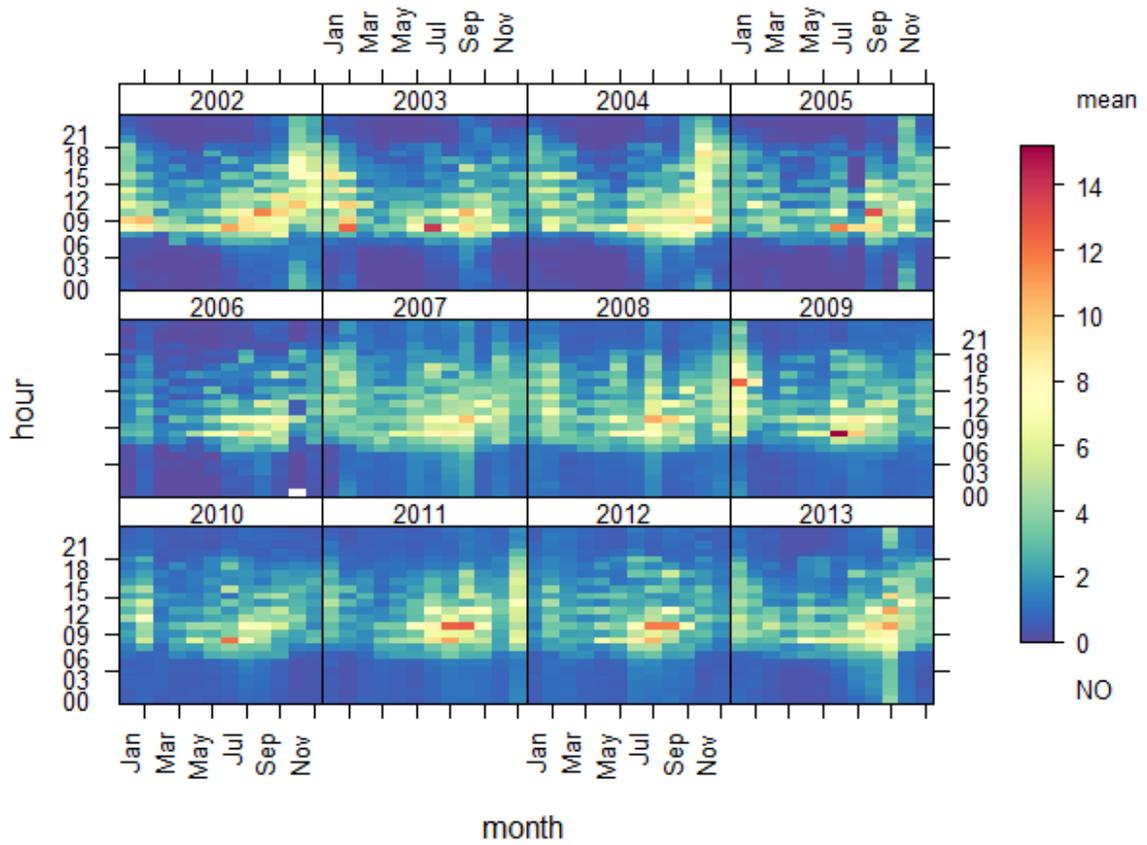
**Time Variation Plot for Squamish TRS, All Available Data**



mean and 95% confidence interval in mean

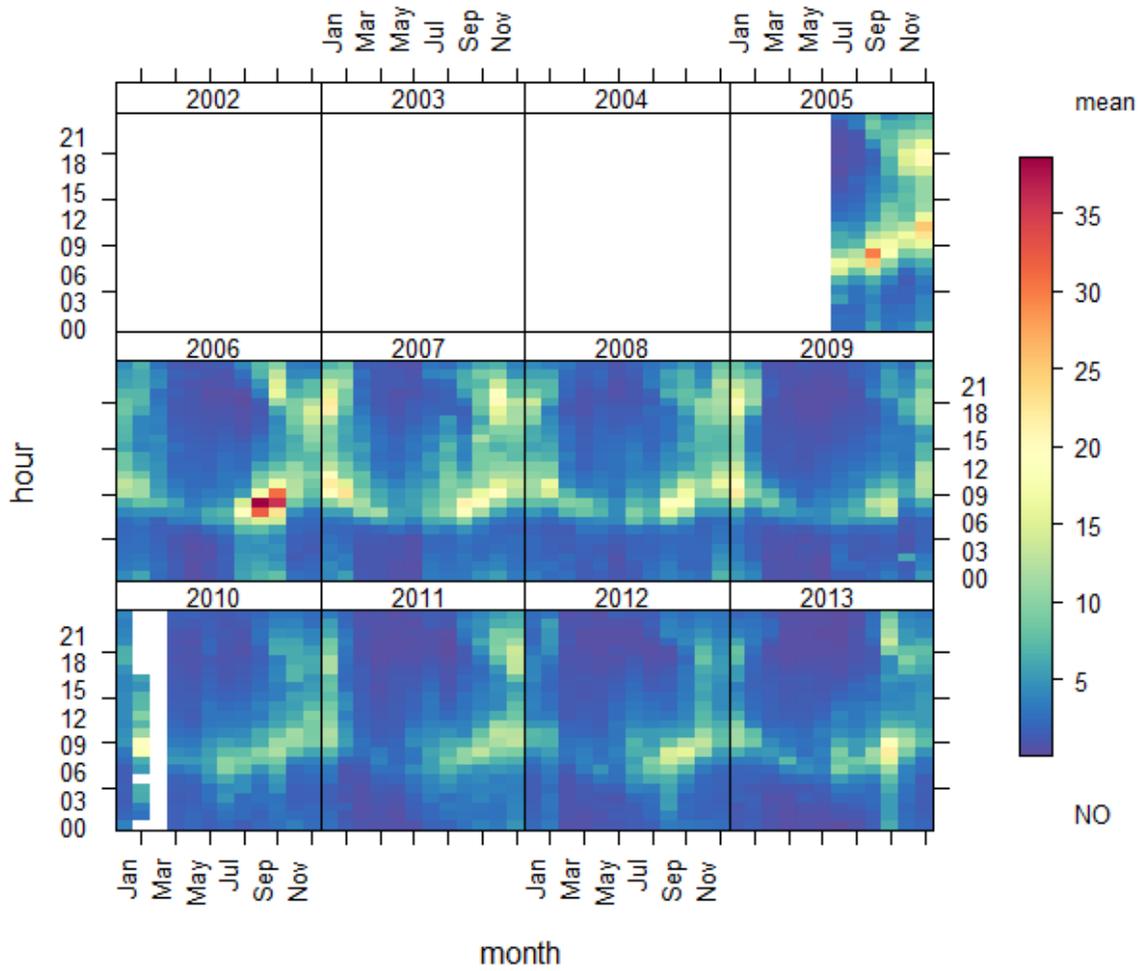
Object E-110 'Time variation plots showing diurnal, weekly and monthly patterns for Squamish TRS'

### Average Hourly Concentrations of Langdale NO for All Available Data



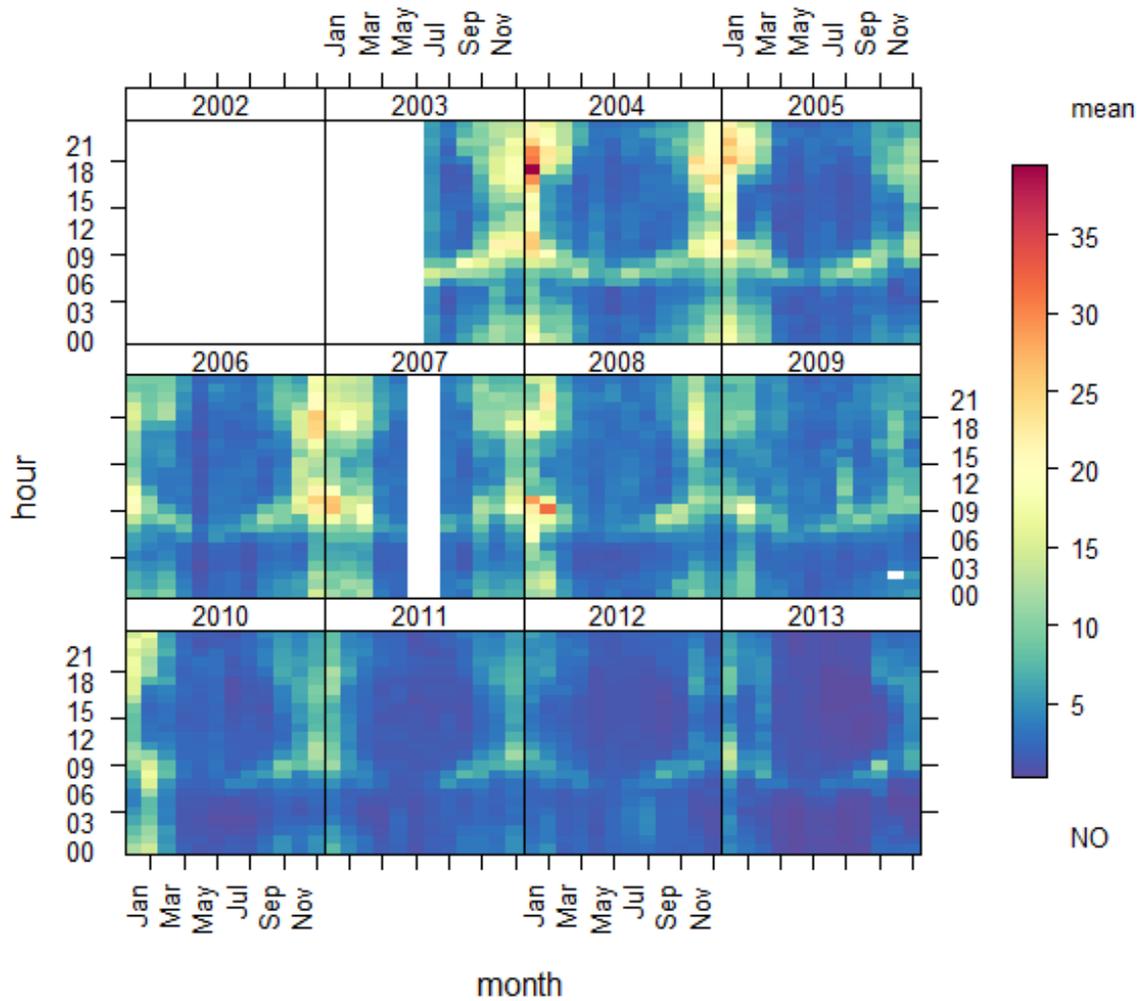
Object E-111 'Daily NO pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish NO for All Available Data



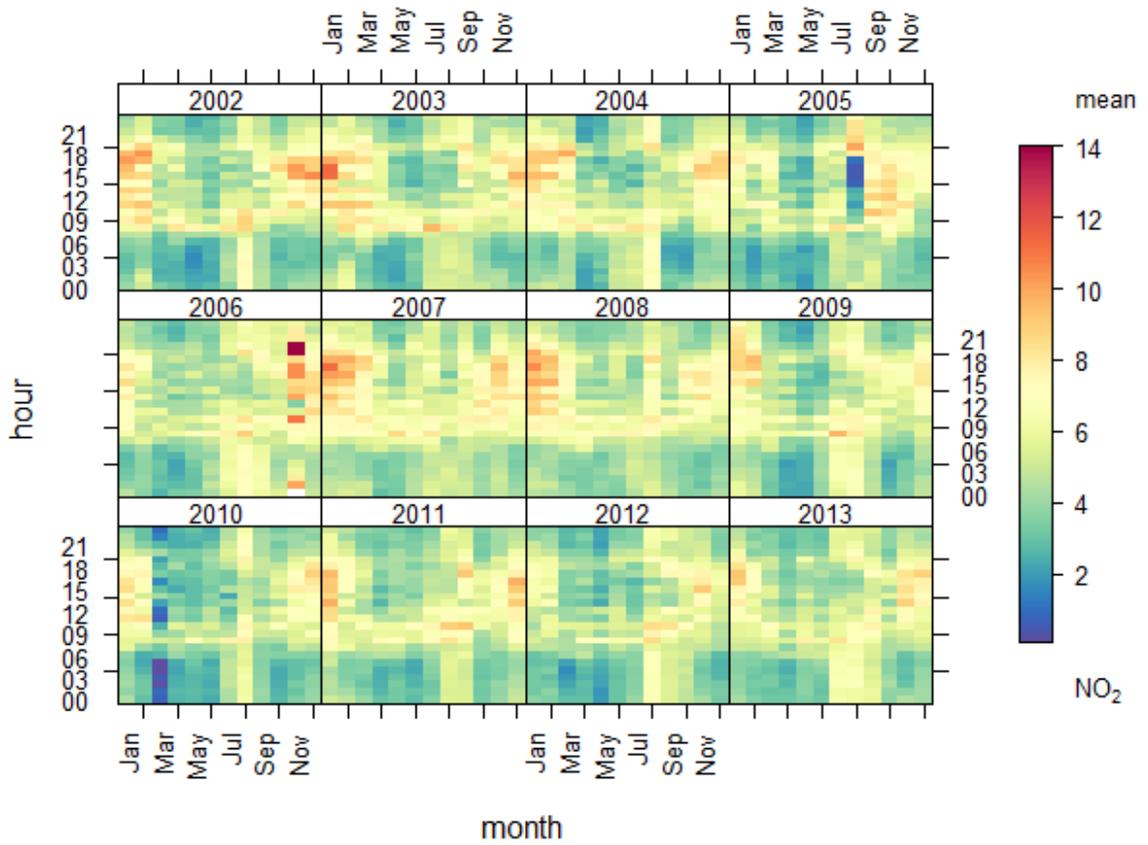
Object E-112 'Daily NO pollutant concentrations for Squamish, averaged over each month of available data'

## Average Hourly Concentrations of Whistler NO for All Available Data



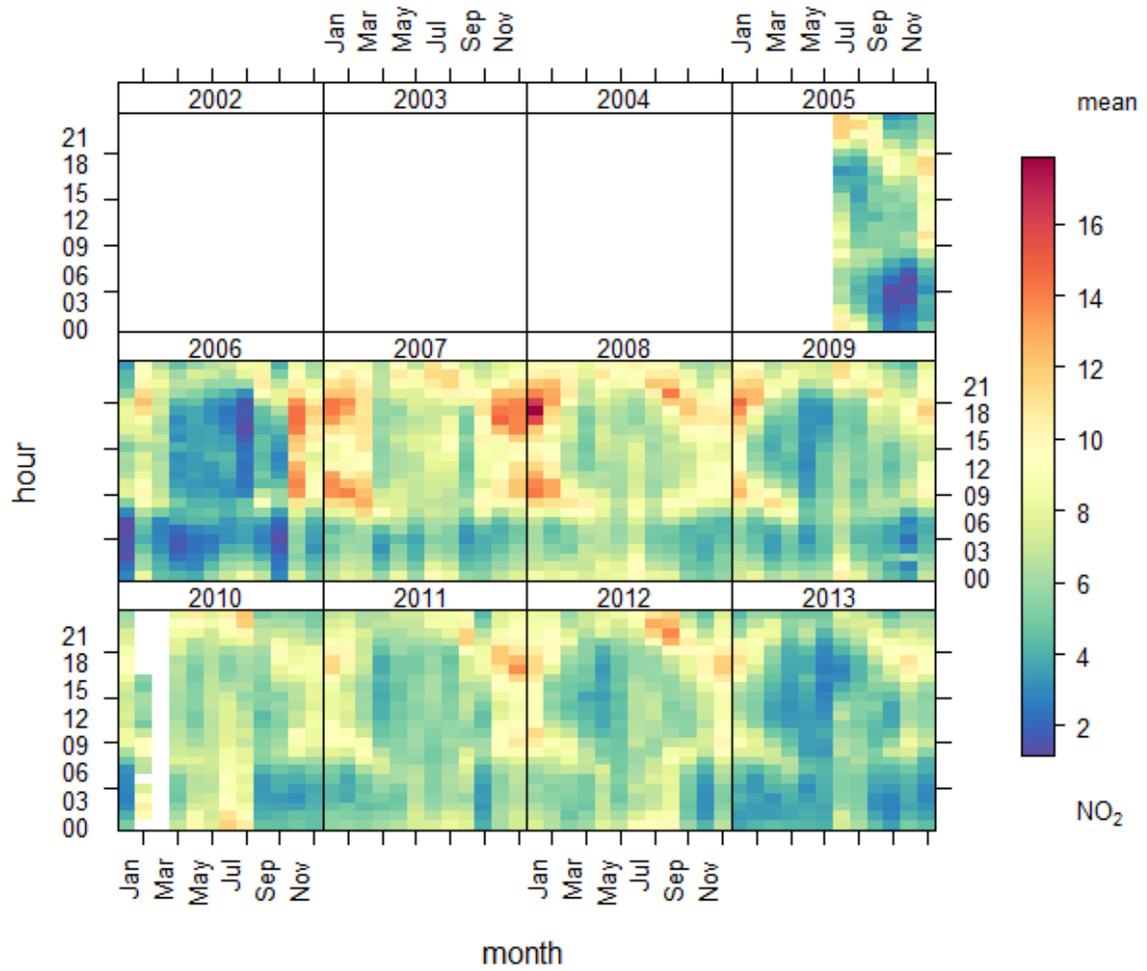
Object E-113 'Daily NO pollutant concentrations for Whistler, averaged over each month of available data'

## Average Hourly Concentrations of Langdale NO<sub>2</sub> for All Available Data



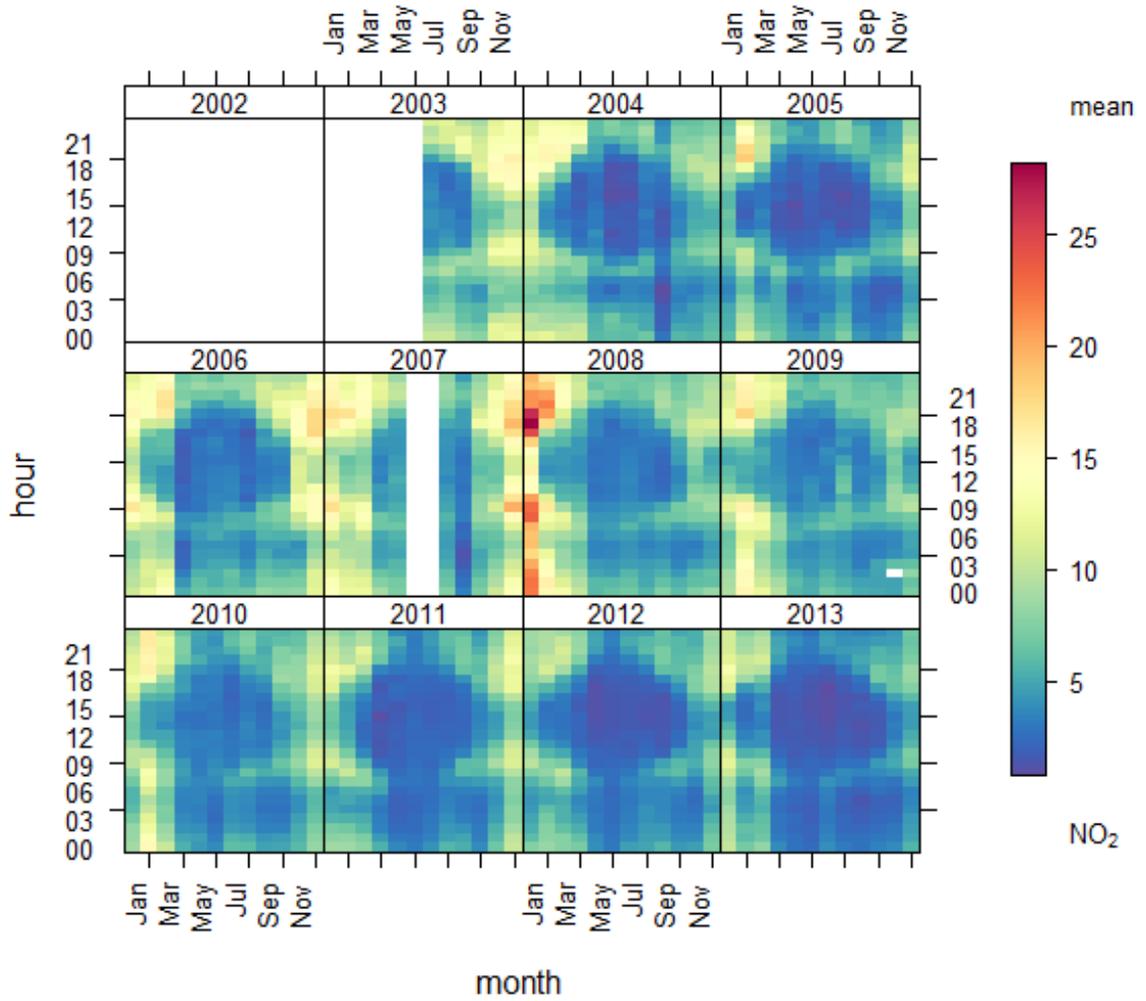
Object E-114 'Daily NO<sub>2</sub> pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish NO<sub>2</sub> for All Available Data



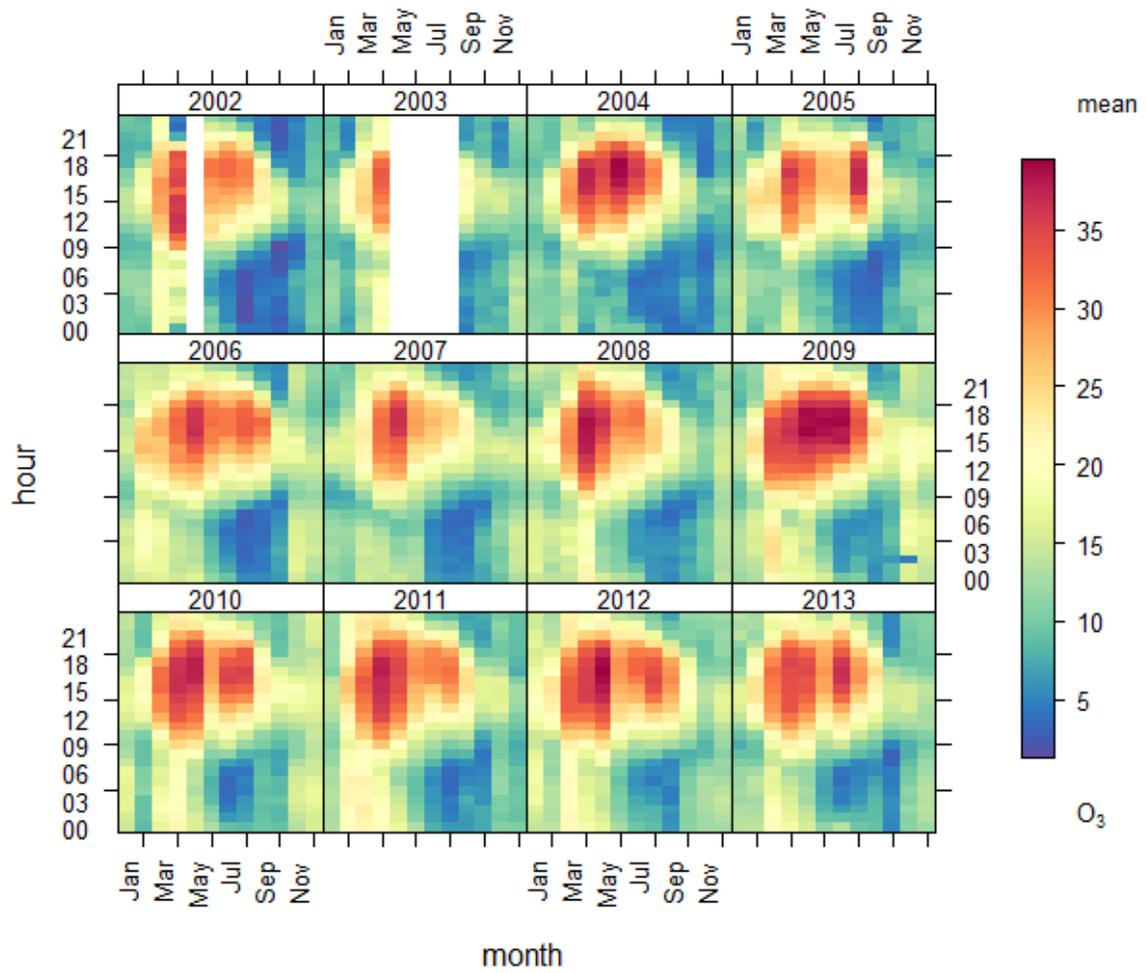
Object E-115 'Daily NO<sub>2</sub> pollutant concentrations for Squamish, averaged over each month of available data'

## Average Hourly Concentrations of Whistler NO<sub>2</sub> for All Available Data



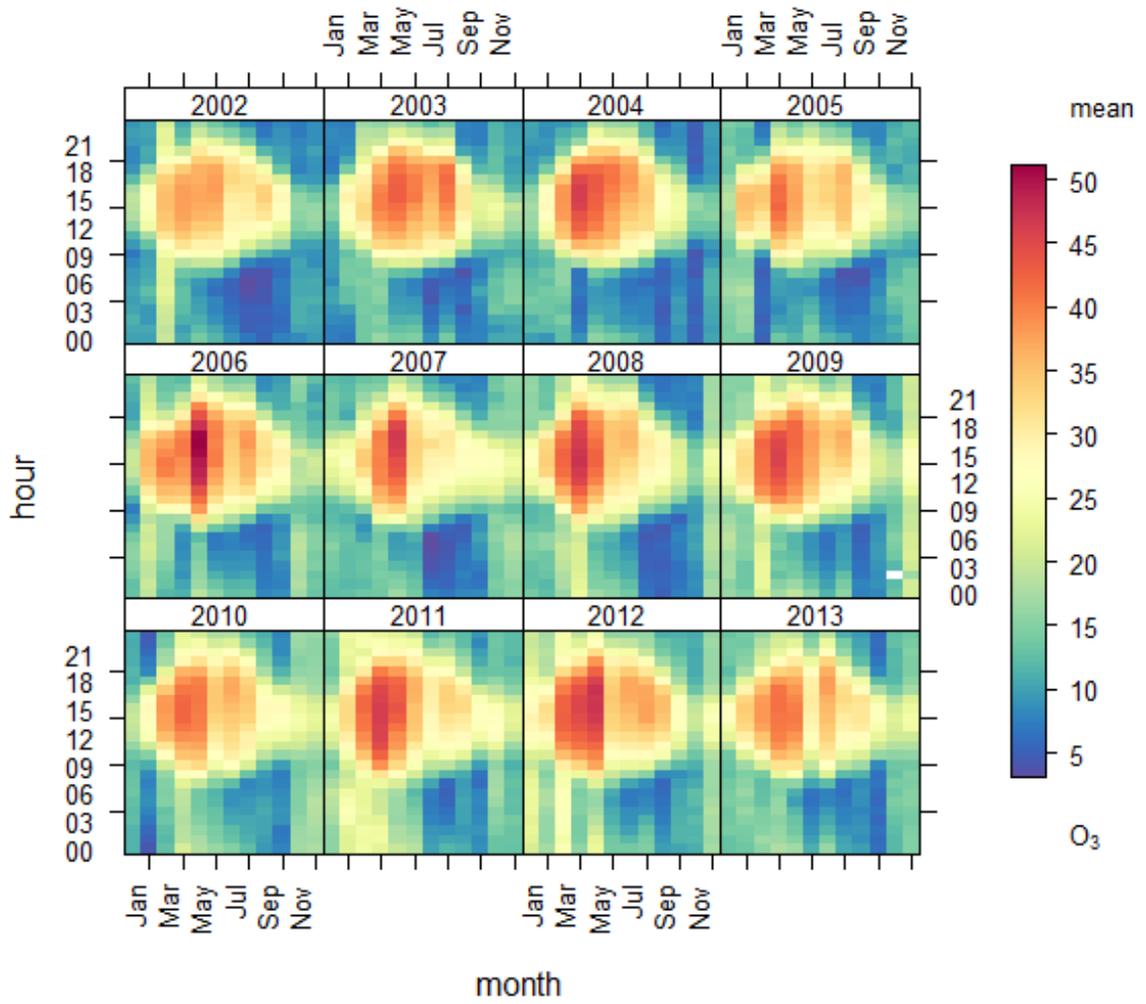
Object E-116 'Daily NO<sub>2</sub> pollutant concentrations for Whistler, averaged over each month of available data'

### Average Hourly Concentrations of Squamish O<sub>3</sub> for All Available Data



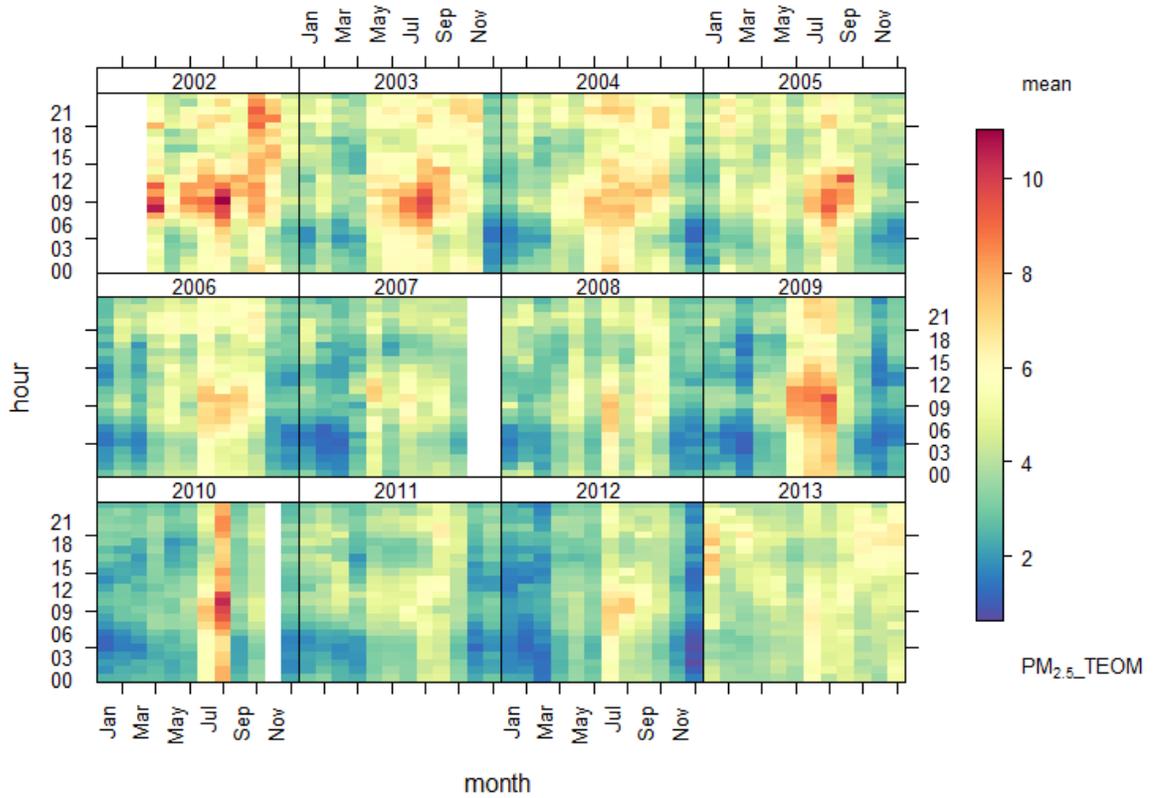
Object E-117 'Daily O<sub>3</sub> pollutant concentrations for Squamish, averaged over each month of available data'

### Average Hourly Concentrations of Whistler O<sub>3</sub> for All Available Data



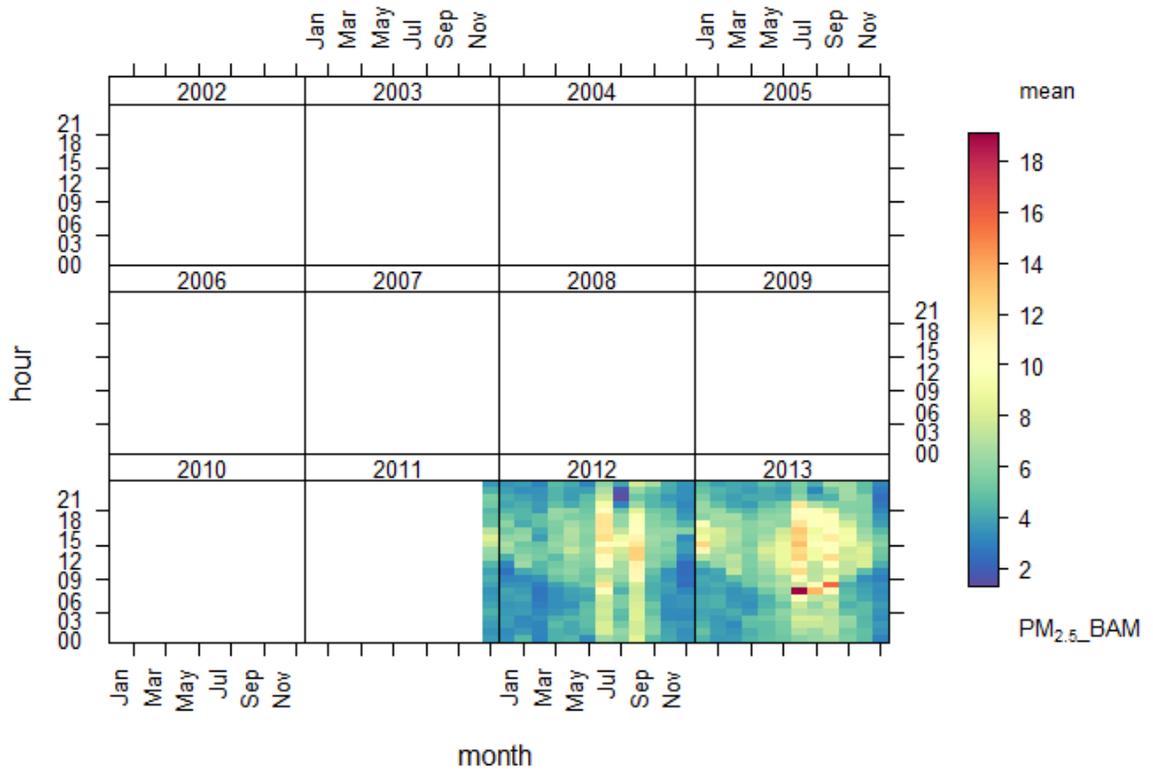
Object E-118 'Daily O<sub>3</sub> pollutant concentrations for Whistler, averaged over each month of available data'

### Average Hourly Concentrations of Horseshoe Bay PM<sub>2.5</sub> (TEOM) for All Available Data



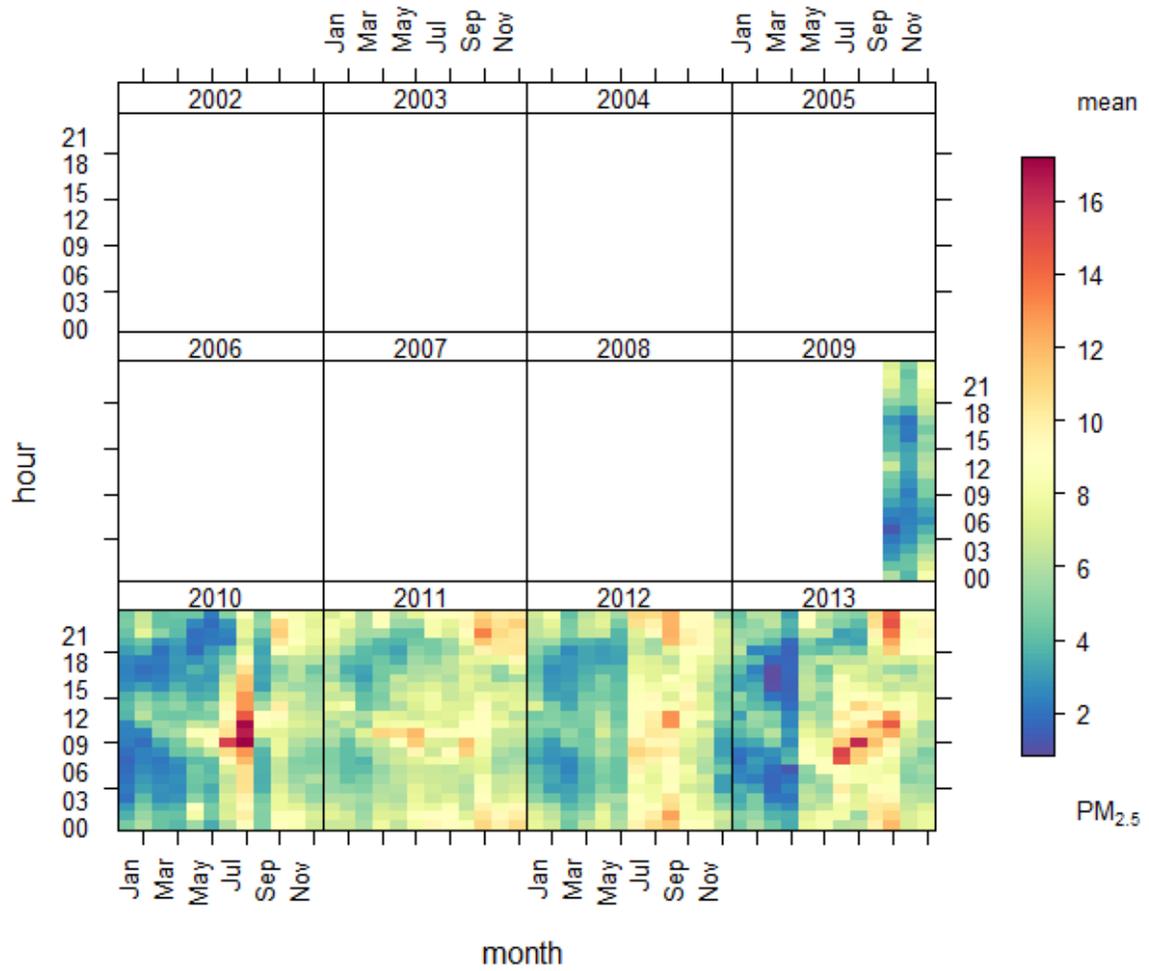
Object E-119 'Daily PM<sub>2.5</sub> TEOM pollutant concentrations for Horseshoe Bay, averaged over each month of available data'

### Average Hourly Concentrations of Langdale PM<sub>2.5</sub> (BAM) for All Available Data



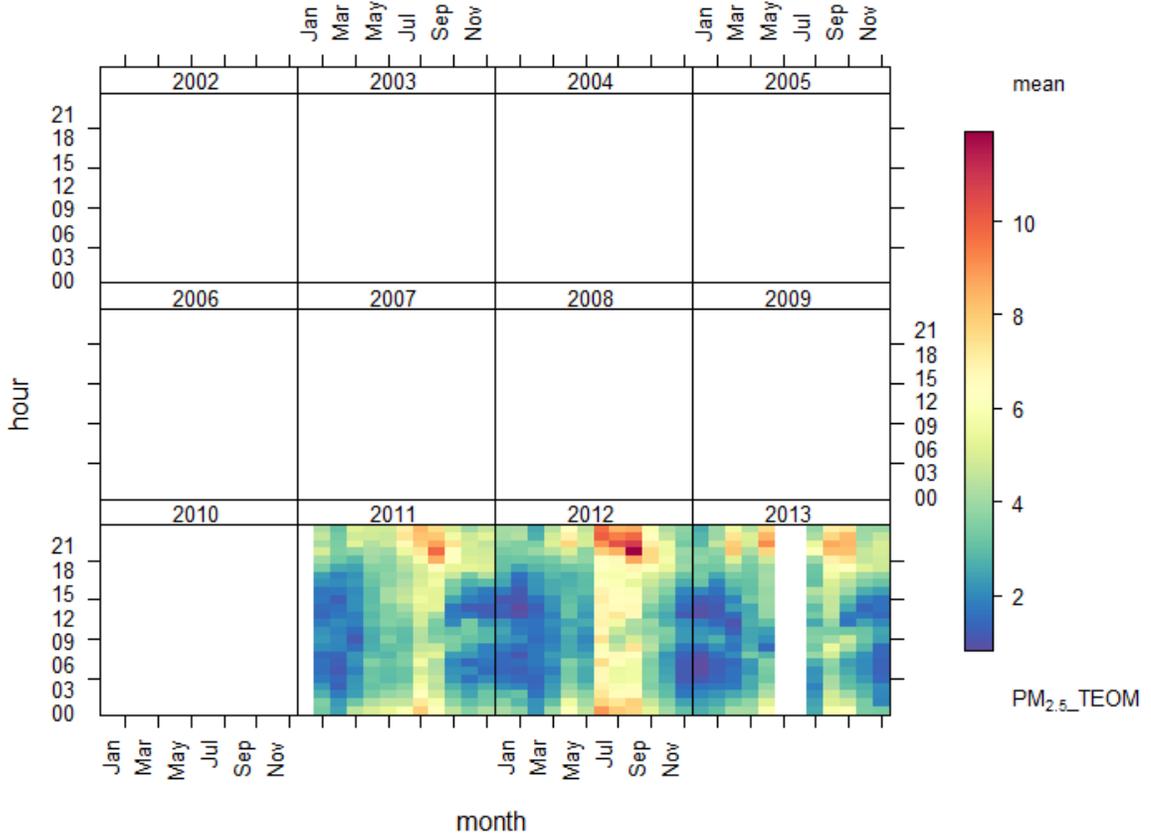
Object E-120 'Daily PM<sub>2.5</sub> BAM pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish PM<sub>2.5</sub> for All Available Data



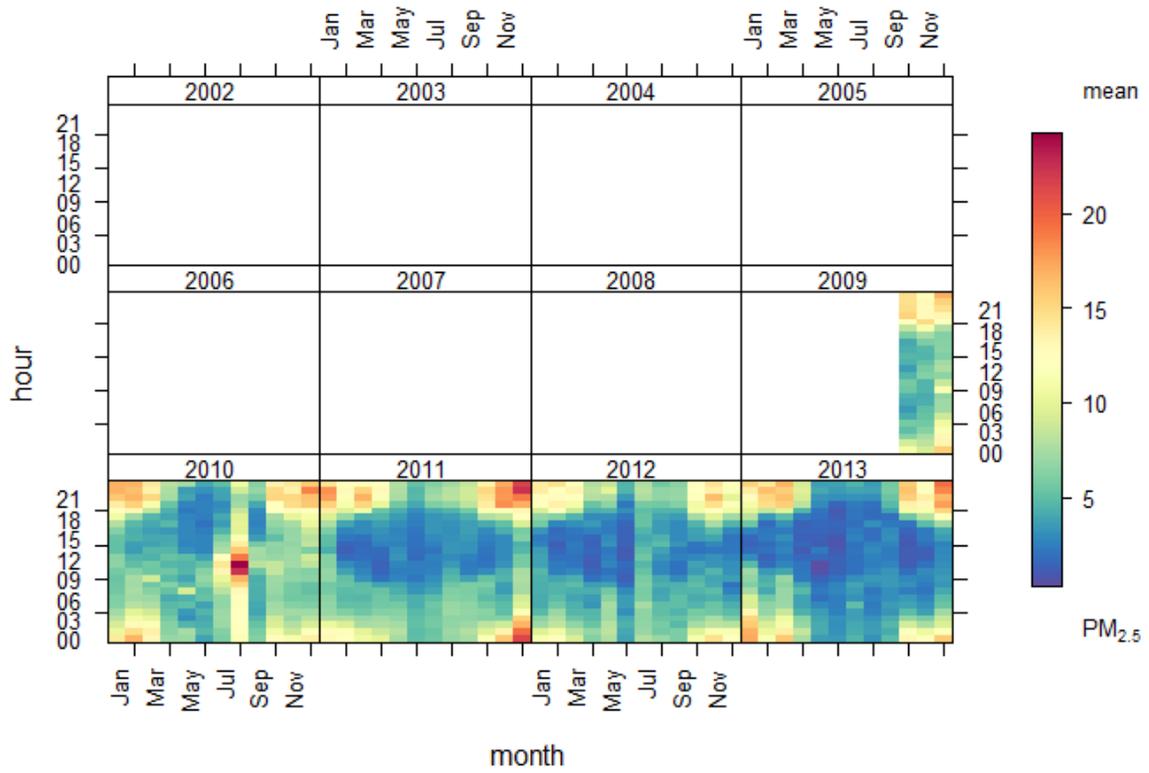
Object E-121 'Daily PM<sub>2.5</sub> BAM pollutant concentrations for Squamish, averaged over each month of available data'

### Average Hourly Concentrations of Squamish PM<sub>2.5</sub> (TEOM) for All Available Data



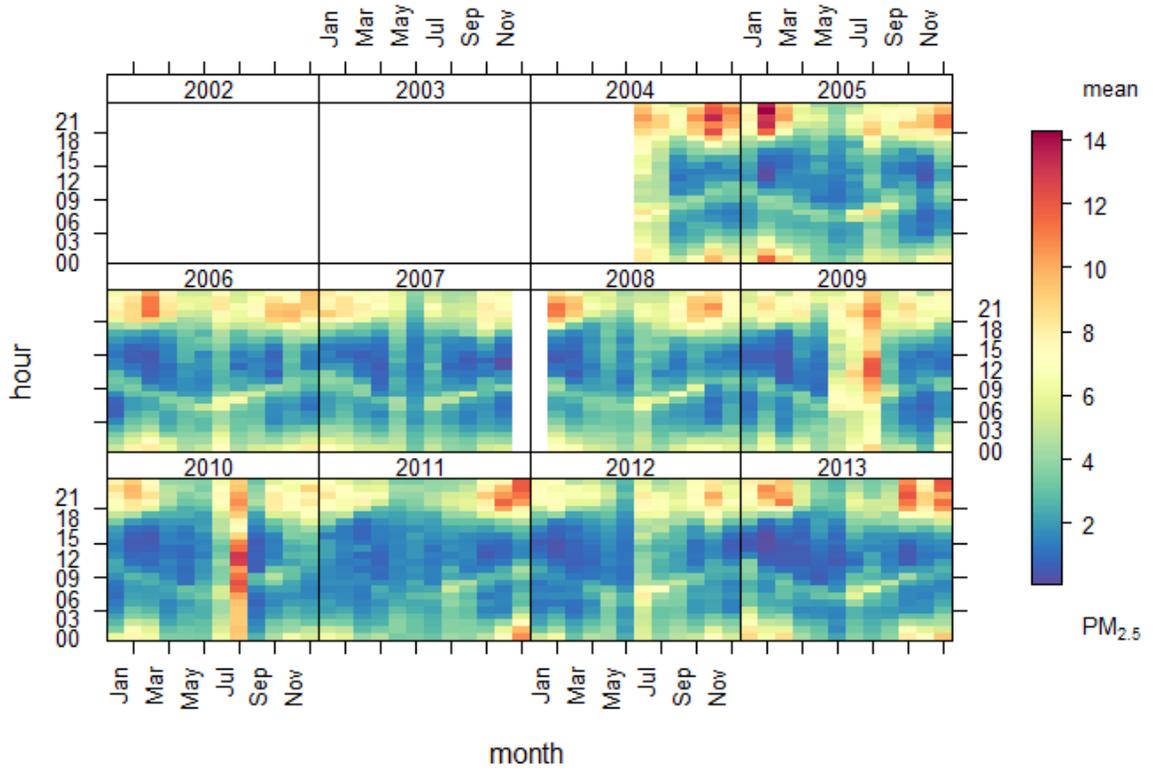
Object E-122 'Daily PM<sub>2.5</sub> TEOM pollutant concentrations for Squamish, averaged over each month of available data'

### Average Hourly Concentrations of Whistler PM<sub>2.5</sub> for All Available Data



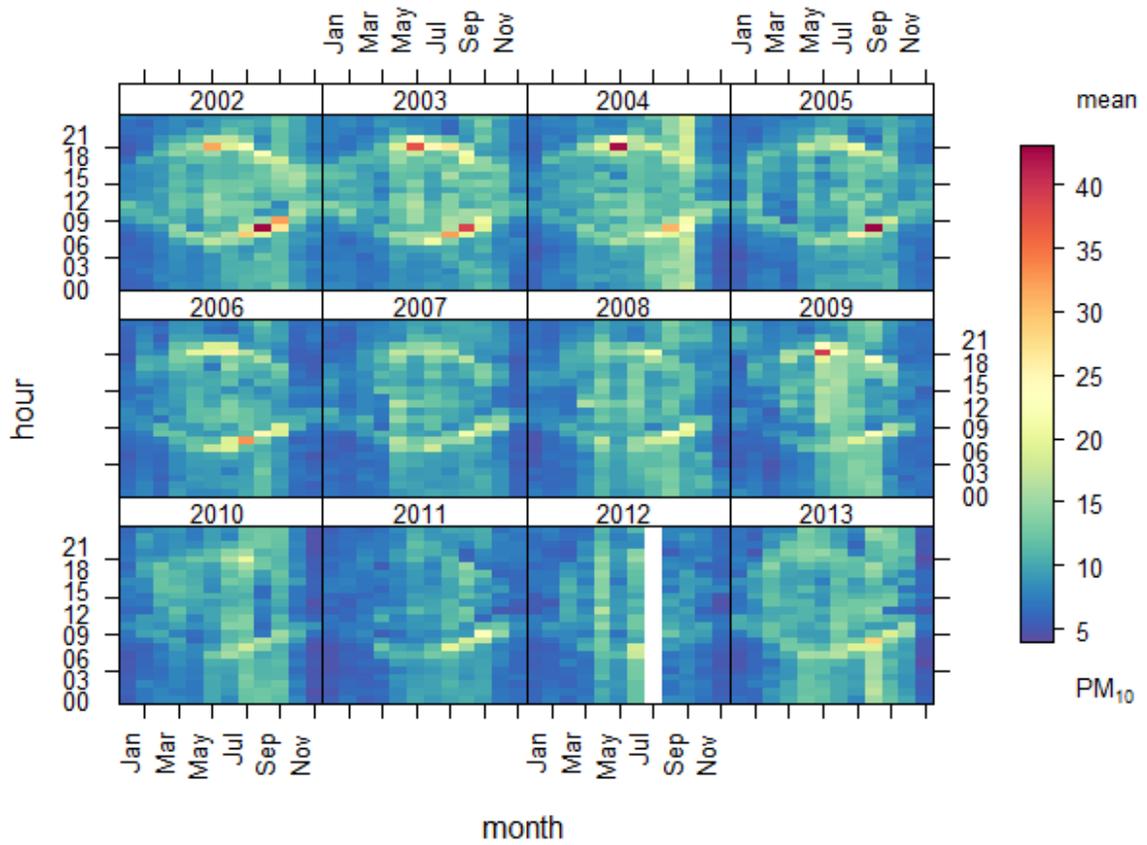
Object E-123 'Daily PM<sub>2.5</sub> BAM pollutant concentrations for Whistler, averaged over each month of available data'

### Average Hourly Concentrations of Whistler PM<sub>2.5</sub> (TEOM) for All Available Data



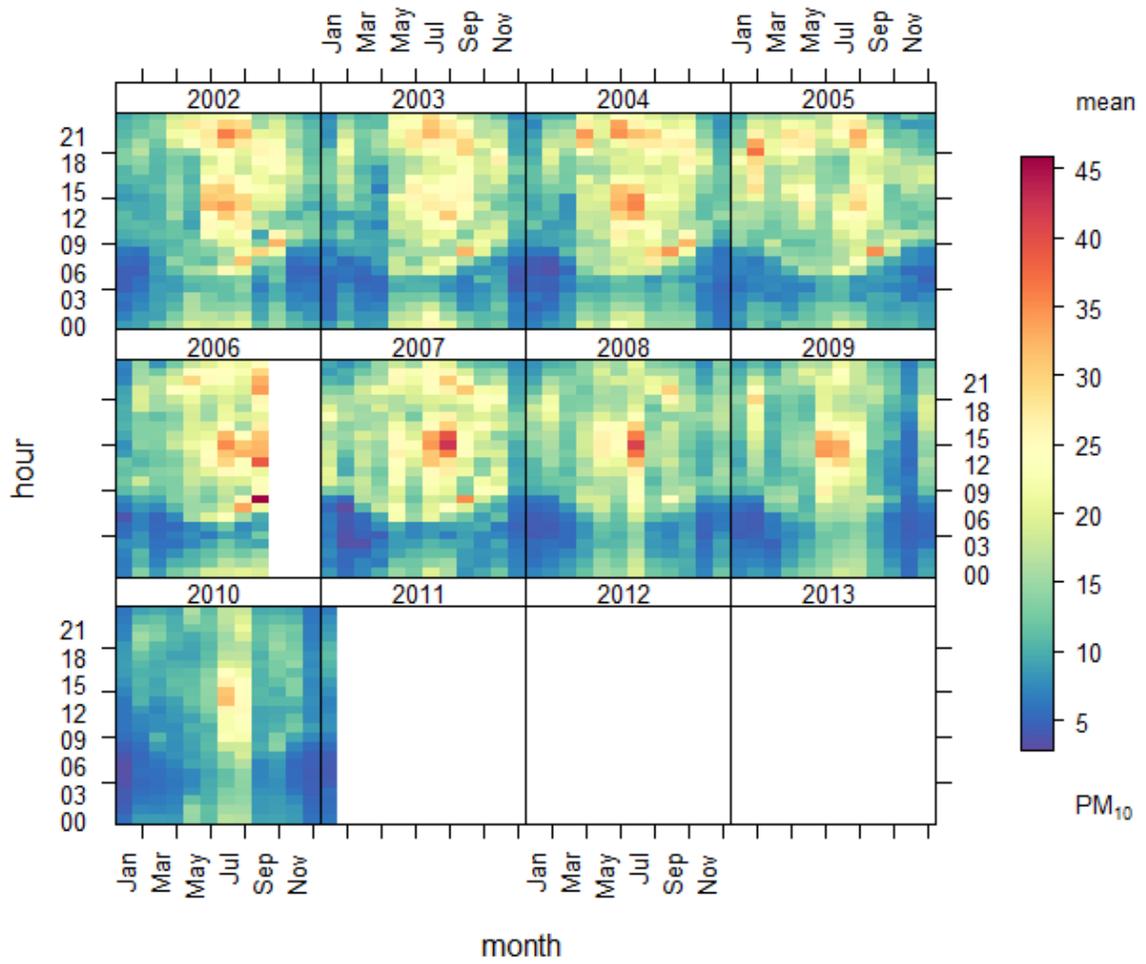
Object E-124 'Daily PM<sub>2.5</sub> TEOM pollutant concentrations for Whistler, averaged over each month of available data'

## Average Hourly Concentrations of Langdale PM<sub>10</sub> for All Available Data



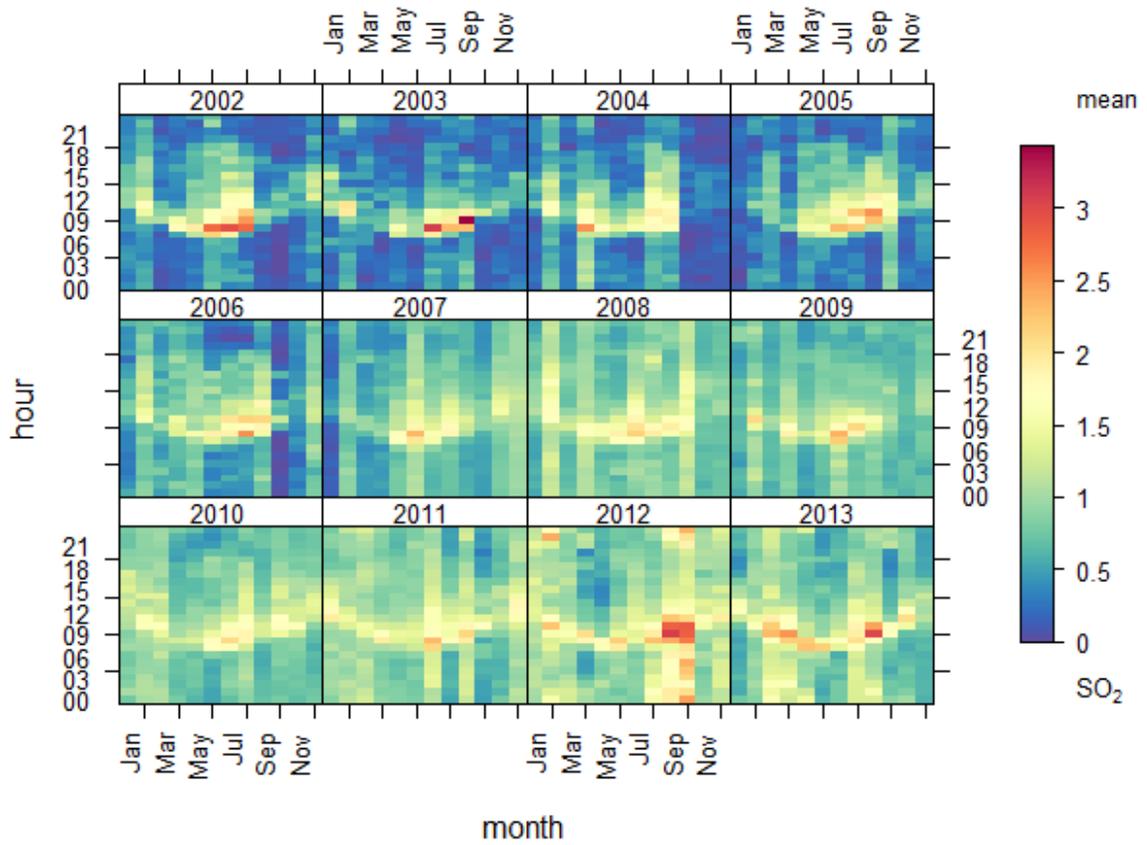
Object E-125 'Daily PM<sub>10</sub> pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish PM<sub>10</sub> for All Available Data



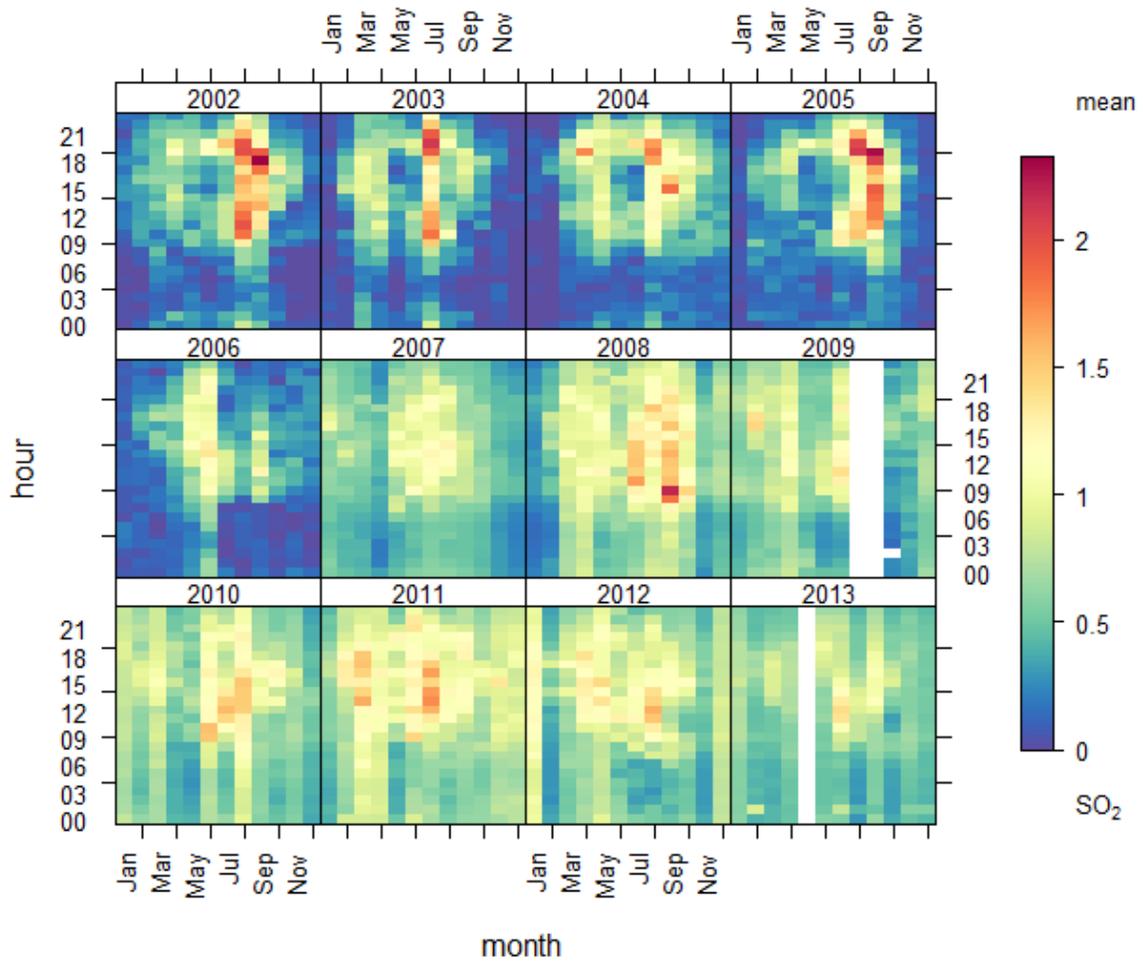
Object E-126 'Daily PM<sub>10</sub> pollutant concentrations for Squamish, averaged over each month of available data'

### Average Hourly Concentrations of Langdale SO<sub>2</sub> for All Available Data



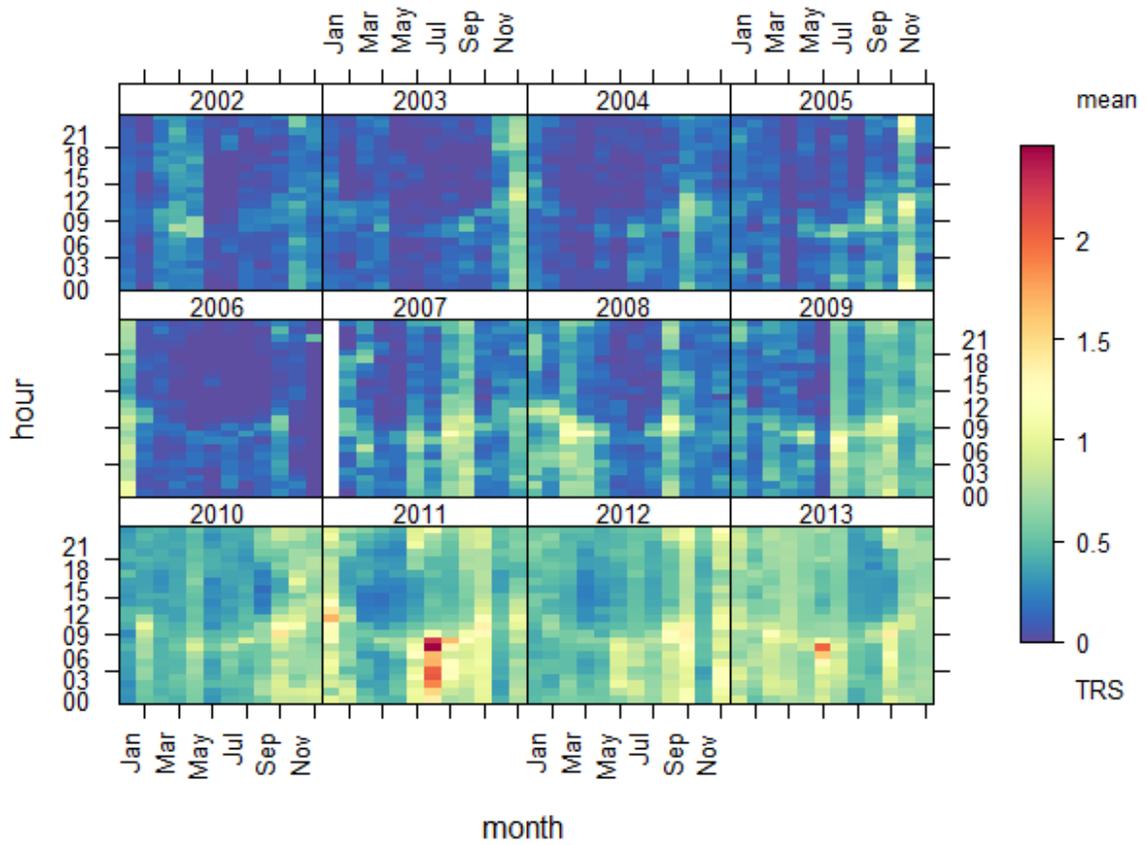
Object E-127 'Daily SO<sub>2</sub> pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish SO<sub>2</sub> for All Available Data



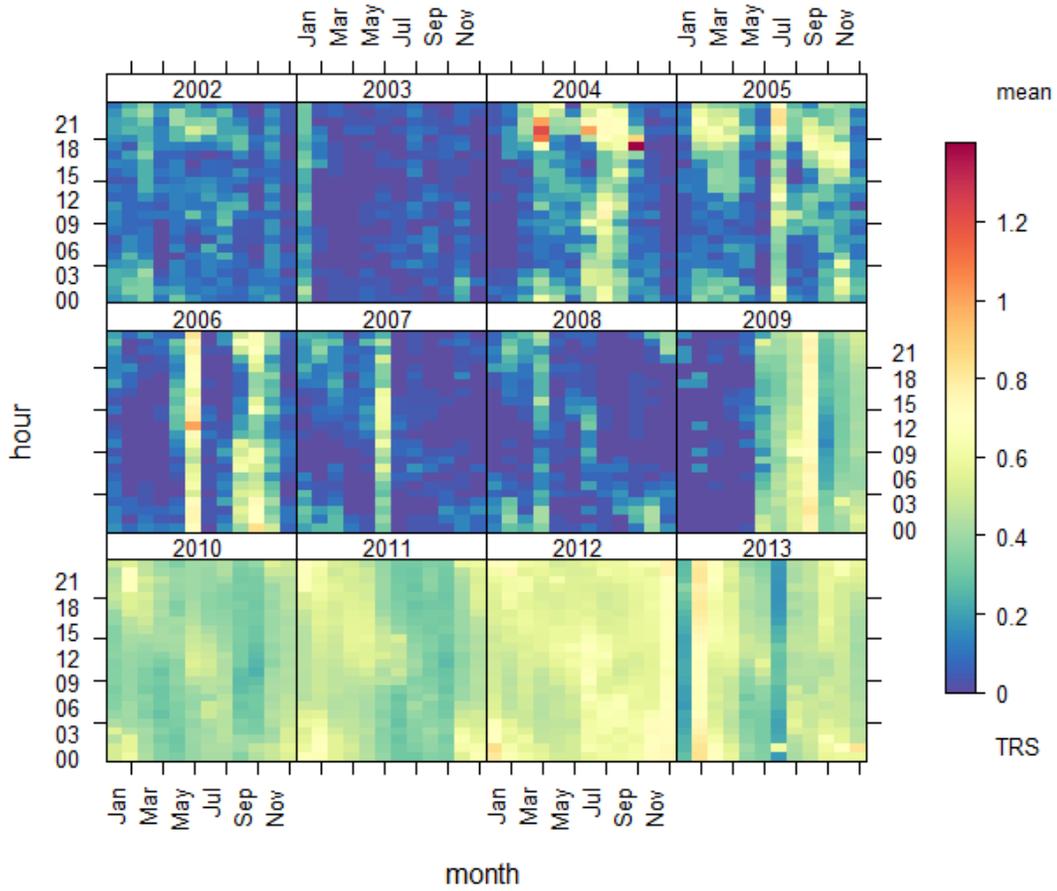
Object E-128 'Daily SO<sub>2</sub> pollutant concentrations for Squamish, averaged over each month of available data'

## Average Hourly Concentrations of Langdale TRS for All Available Data



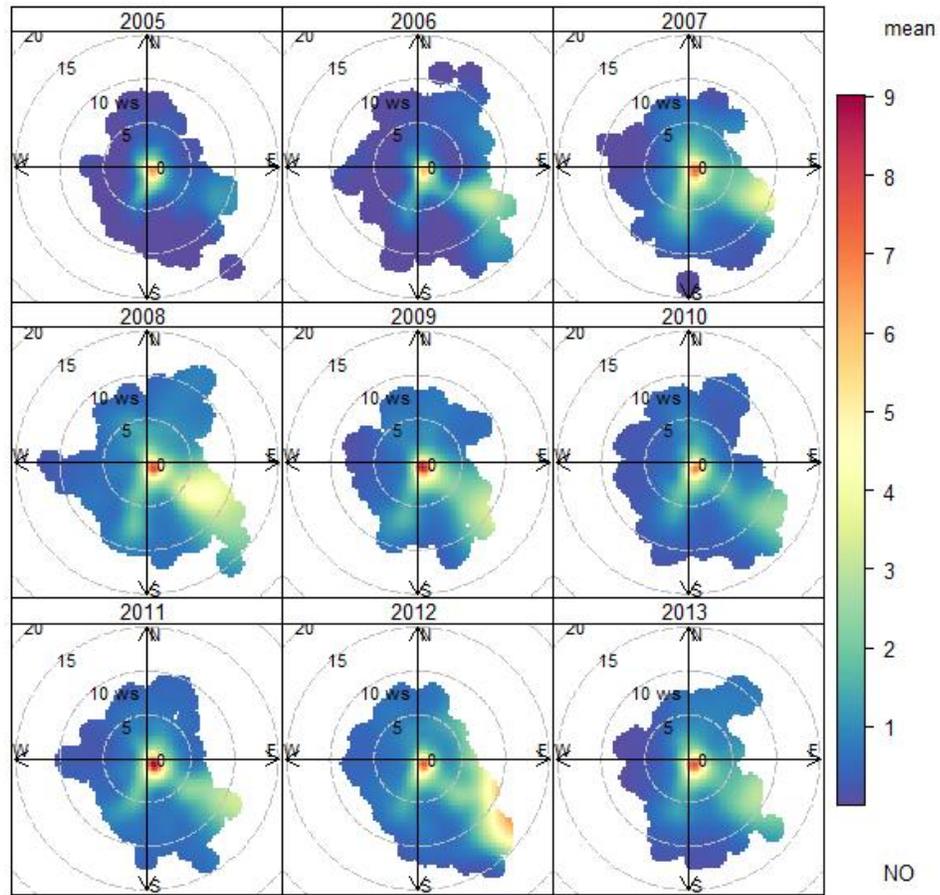
Object E-129 'Daily TRS pollutant concentrations for Langdale, averaged over each month of available data'

### Average Hourly Concentrations of Squamish TRS for All Available Data



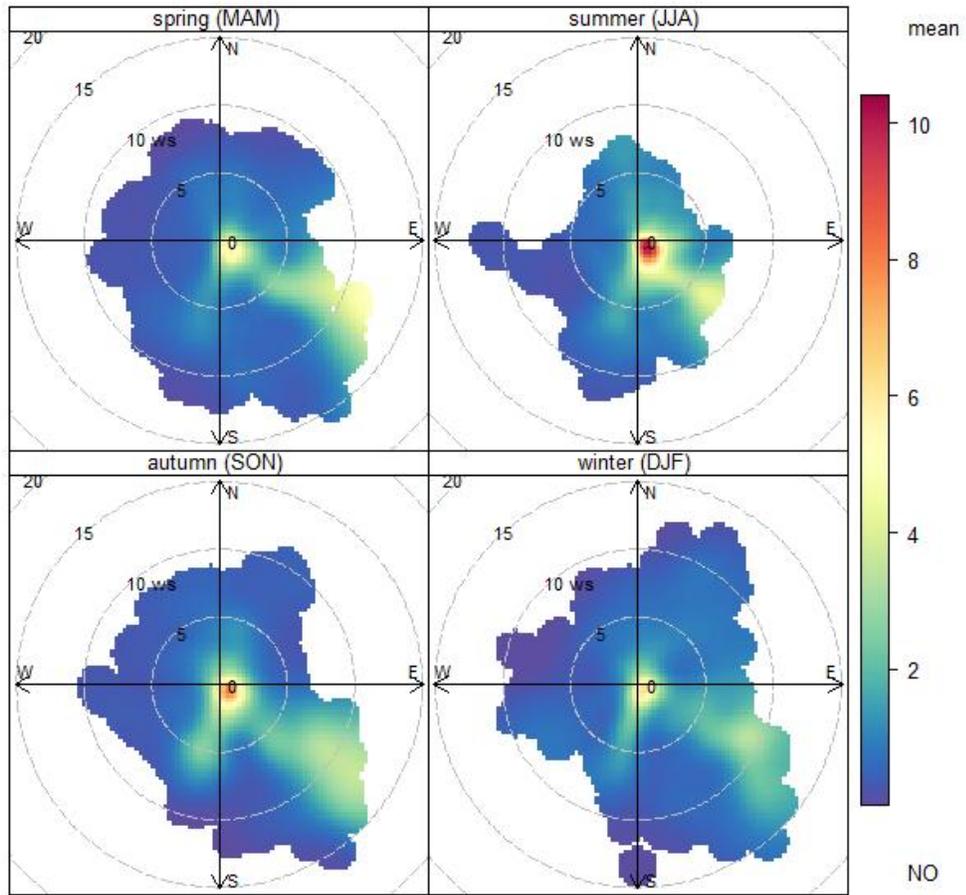
Object E-130 'Daily TRS pollutant concentrations for Squamish averaged over each month of available data'

### Annual Pollution Rose for Langdale NO



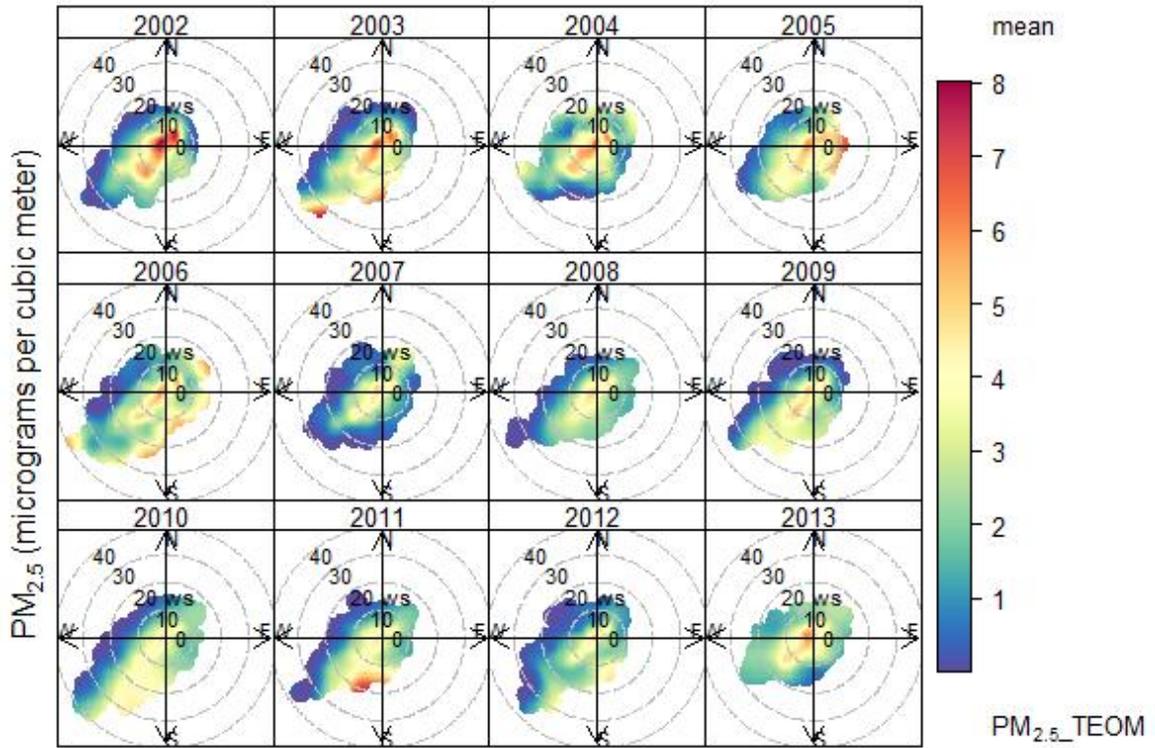
Object E-131 'Pollution roses for NO at Langdale, showing each average year of data'

### Seasonal Pollution Rose for Langdale NO



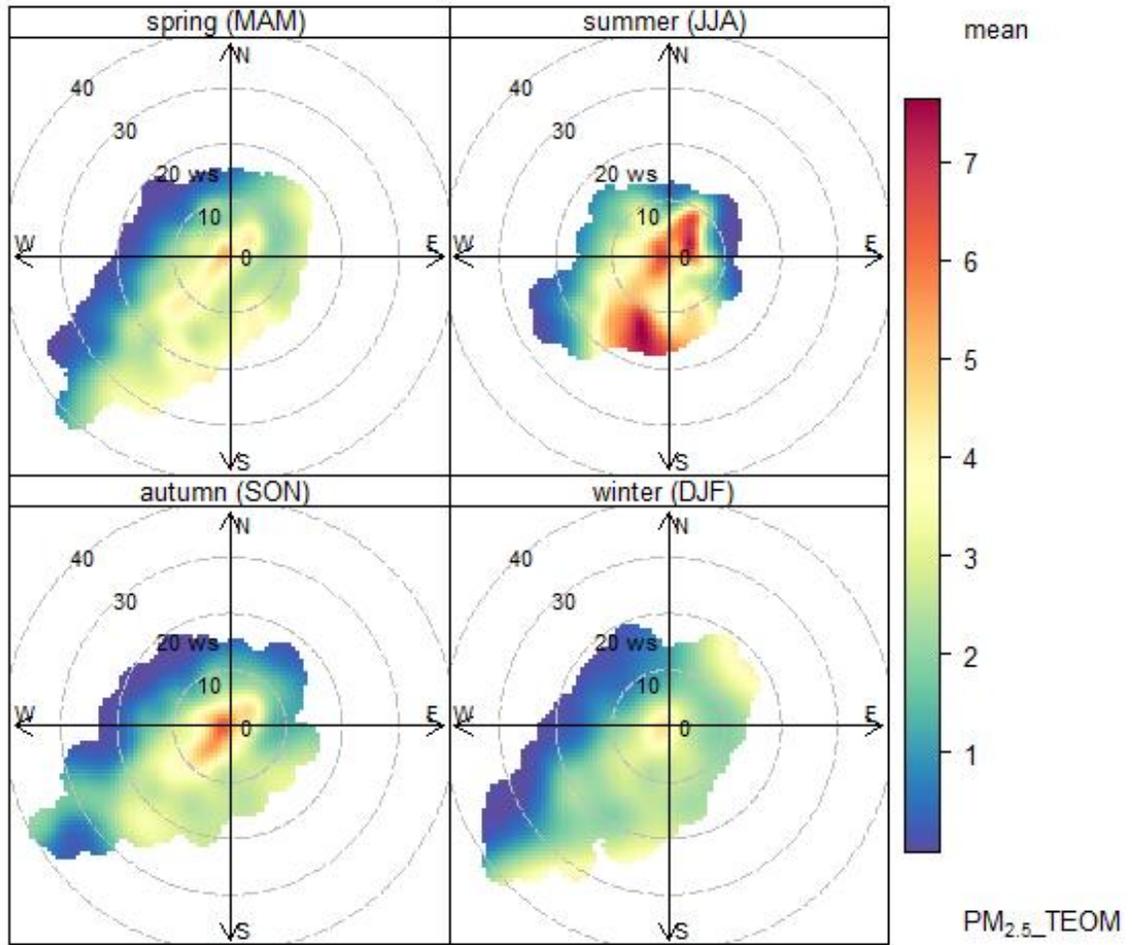
Object E-132 'Pollution roses for NO at Langdale, showing seasonal patterns'

### Annual Pollution Rose for Horseshoe Bay PM<sub>2.5</sub> (TEOM)



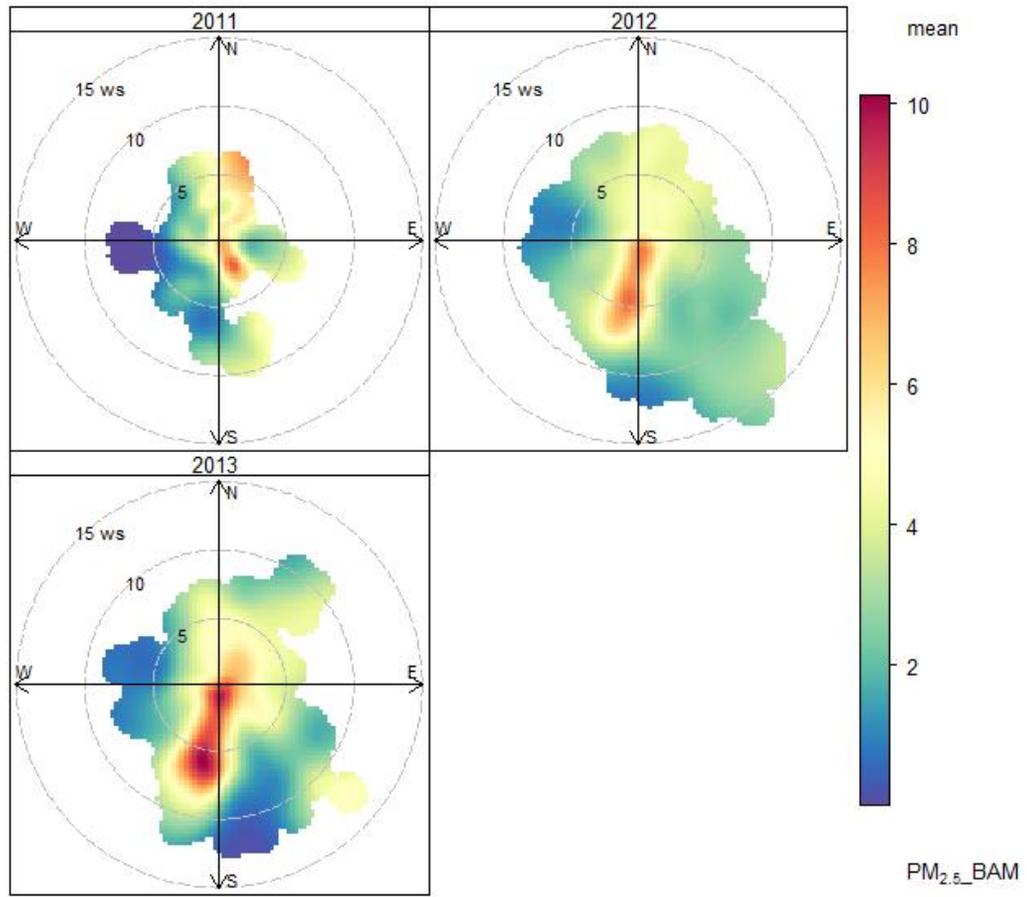
Object E-133 'Pollution roses for PM<sub>2.5</sub> at Horseshoe Bay, showing each average year of data'

### Seasonal Pollution Rose for Horseshoe Bay PM<sub>2.5</sub> (TEOM)



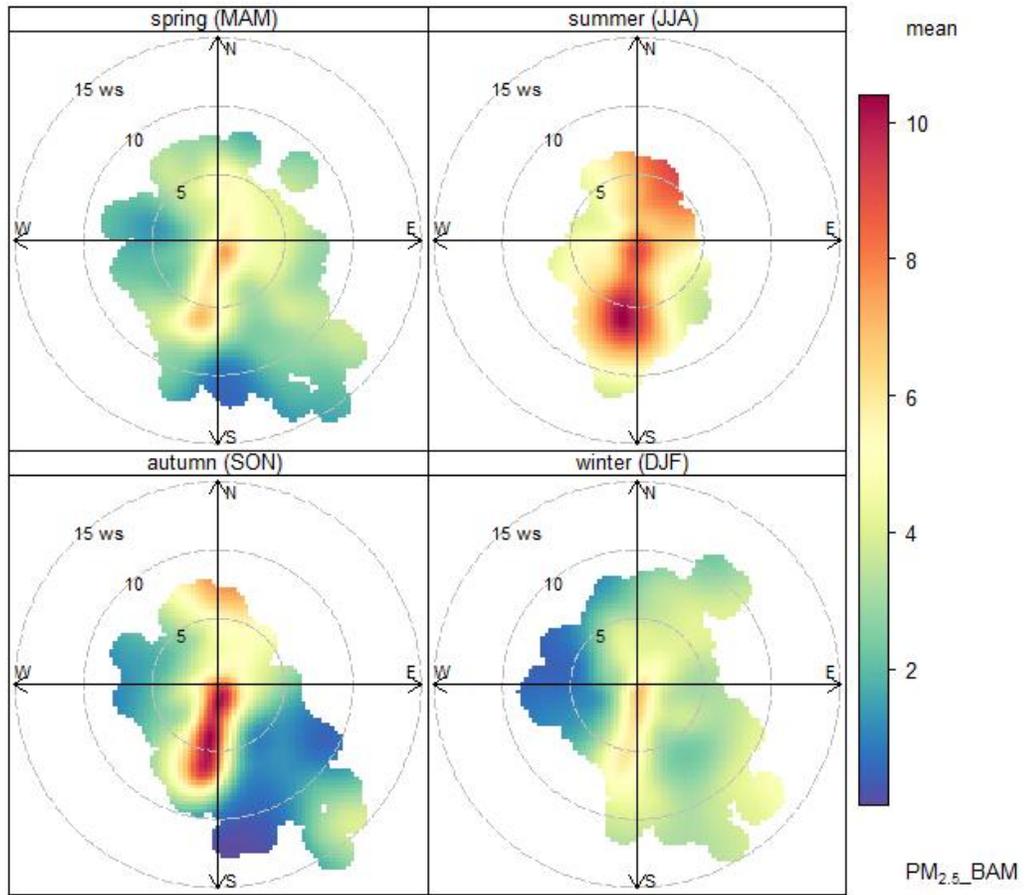
Object E-134 'Pollution roses for PM<sub>2.5</sub> at Horseshoe Bay, showing each average year of data'

### Annual Pollution Rose for Langdale PM<sub>2.5</sub> (BAM)



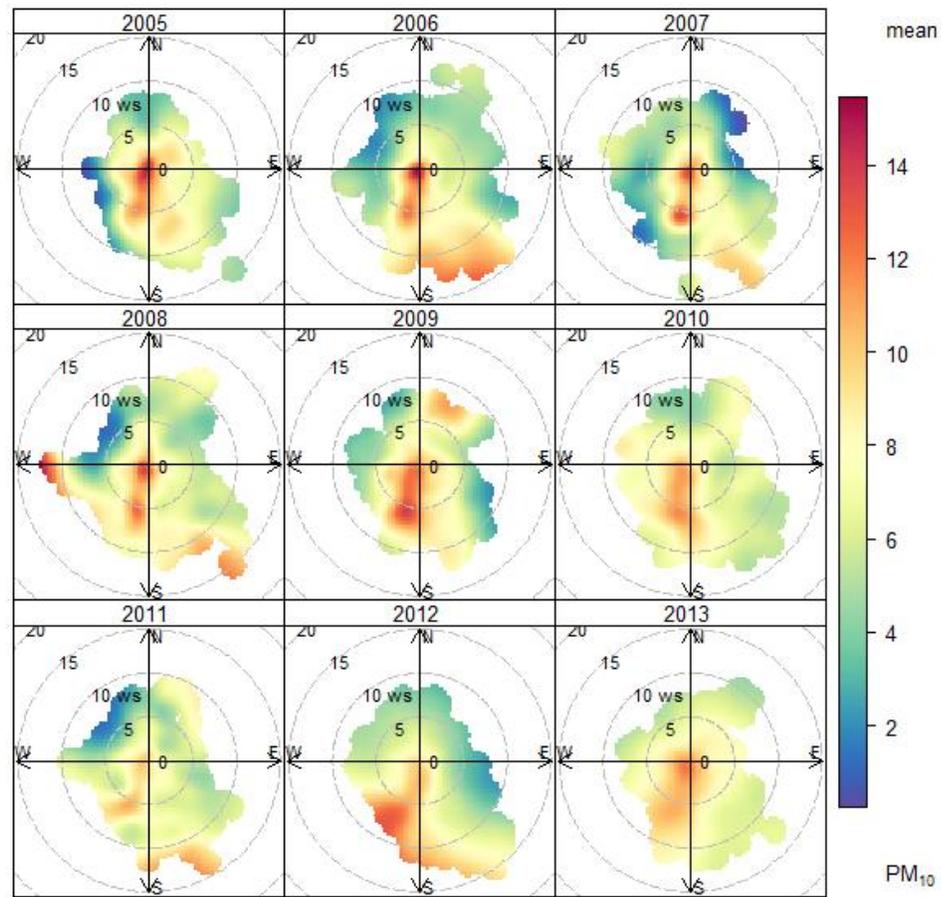
Object E-135 'Pollution roses for PM<sub>2.5</sub> BAM at Langdale, showing each average year of data'

### Seasonal Pollution Rose for Langdale PM<sub>2.5</sub> (BAM)



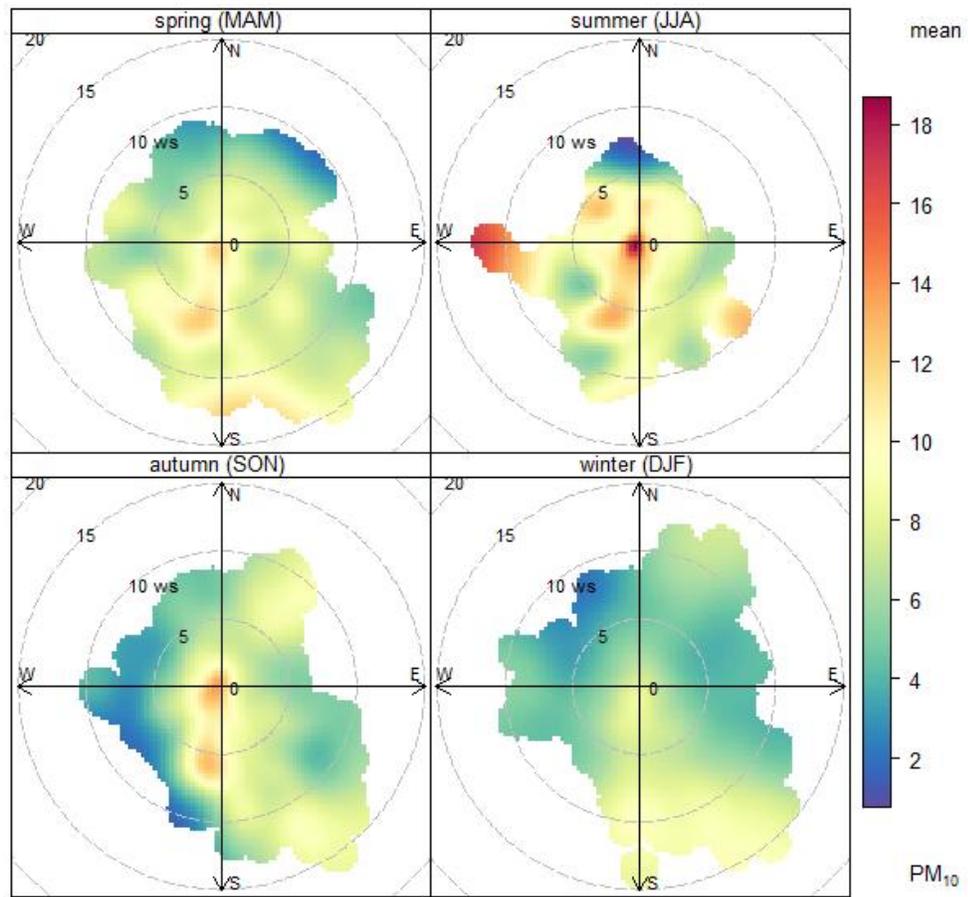
Object E-136 'Pollution roses for PM<sub>2.5</sub> BAM at Langdale, showing each season'

### Annual Pollution Rose for Langdale PM<sub>10</sub>



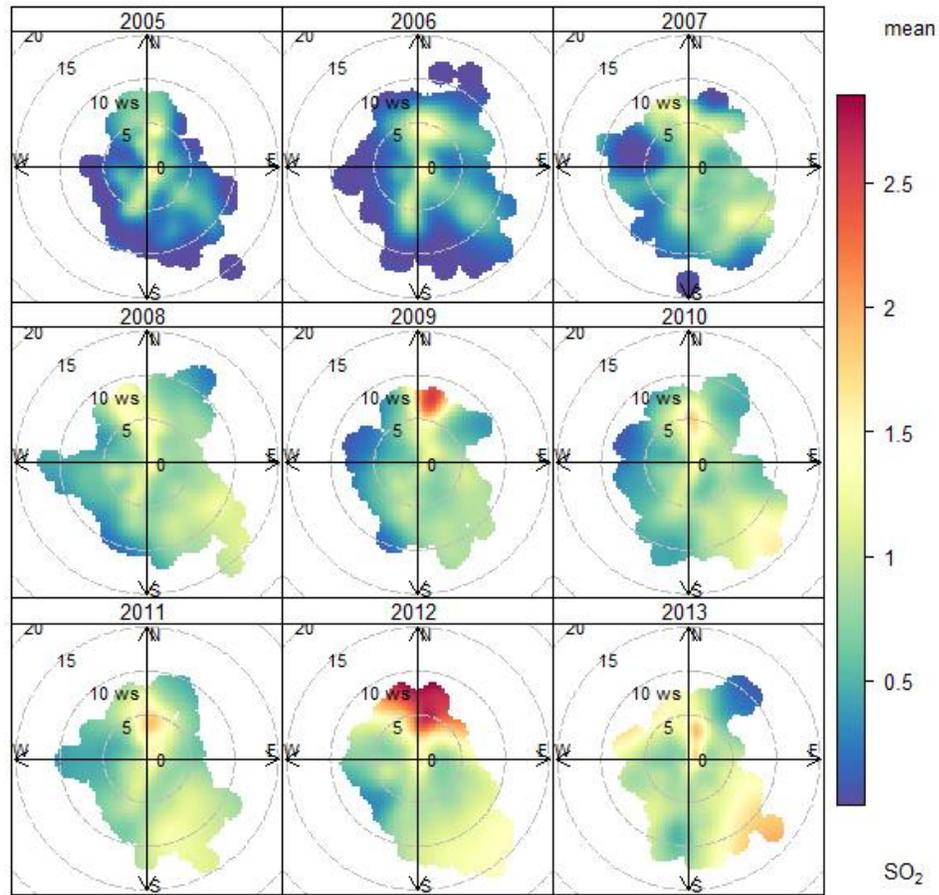
Object E-137 'Pollution roses for PM<sub>10</sub> at Langdale, showing each average year of data'

### Seasonal Pollution Rose for Langdale PM<sub>10</sub>



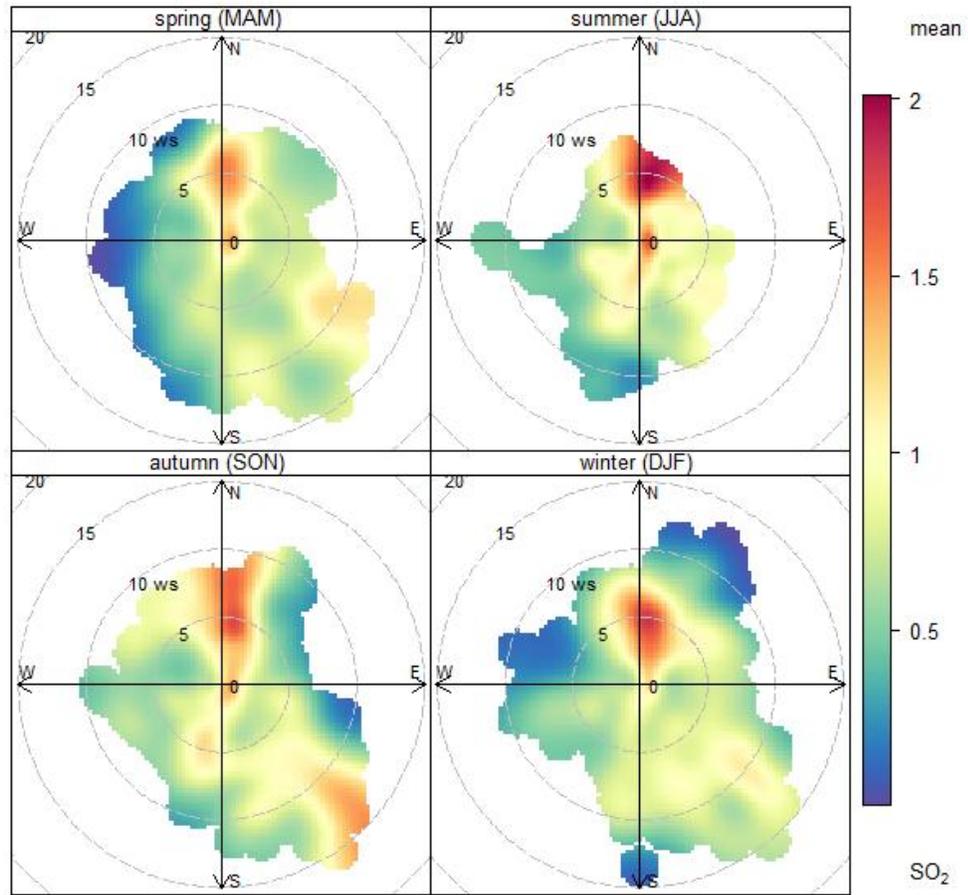
Object E-138 'Pollution roses for PM<sub>10</sub> at Langdale, showing each season'

### Annual Pollution Rose for Langdale SO<sub>2</sub>



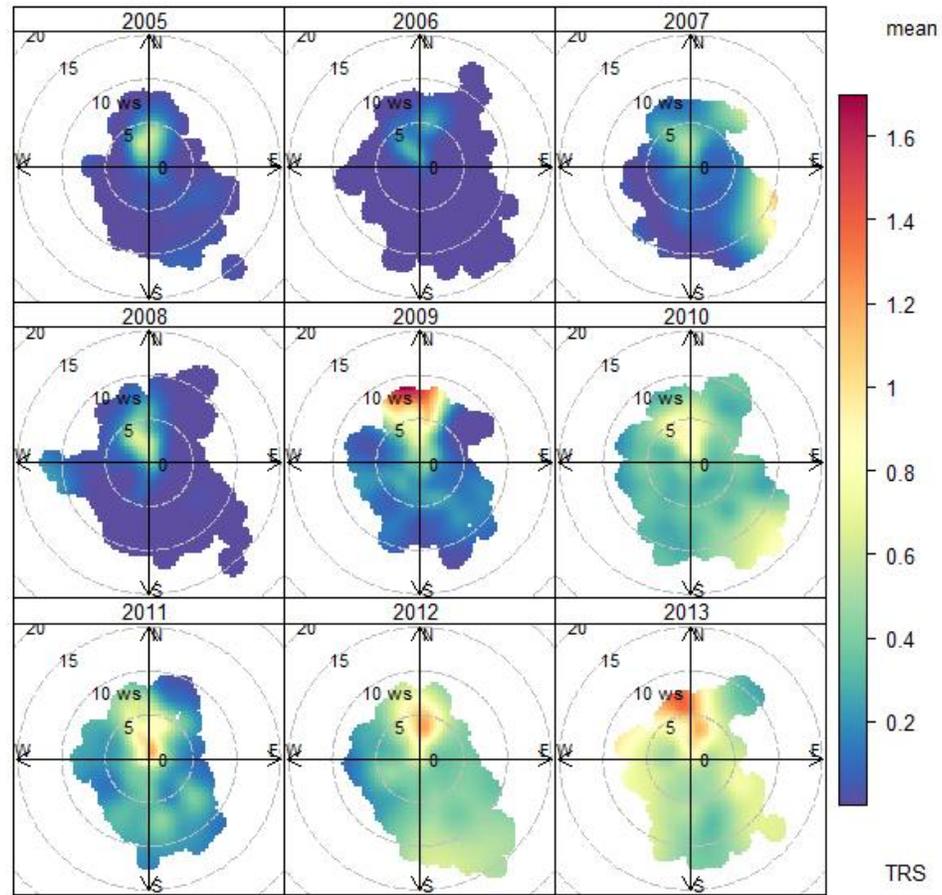
Object E-139 'Pollution roses for SO<sub>2</sub> at Langdale, showing each average year of data'

### Seasonal Pollution Rose for Langdale SO<sub>2</sub>



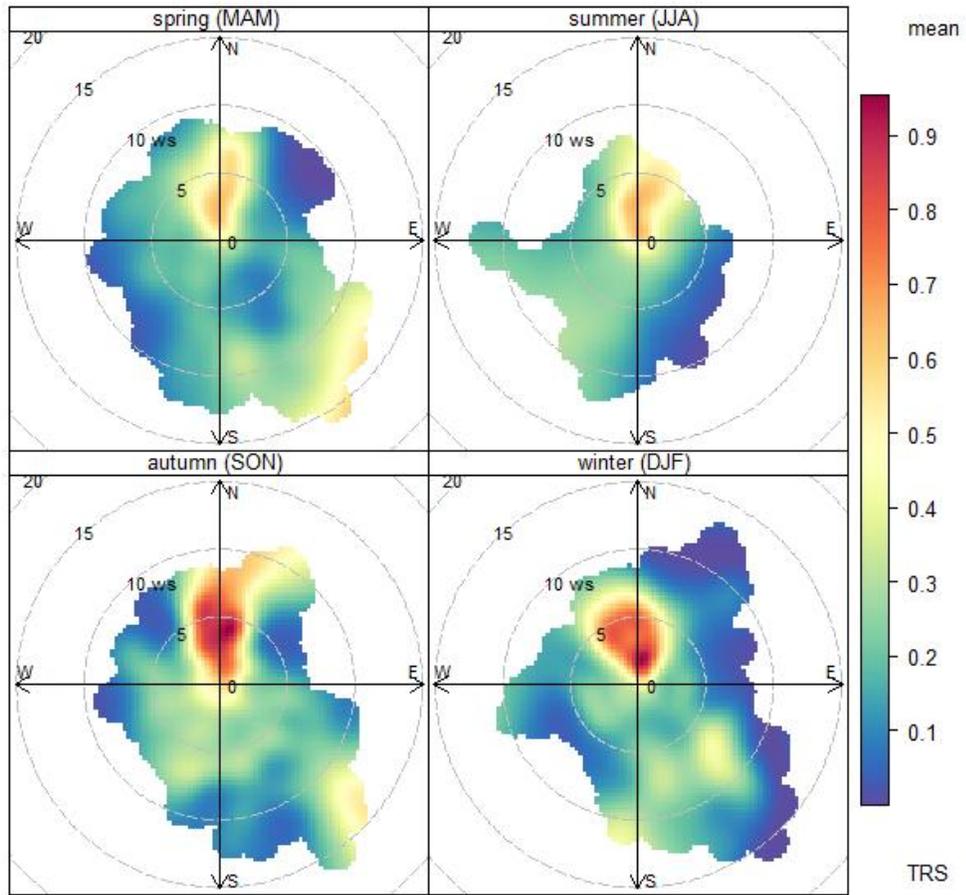
Object E-140 'Pollution roses for SO<sub>2</sub> at Langdale, showing each season'

### Annual Pollution Rose for Langdale TRS



Object E-141 'Pollution roses for TRS at Langdale, showing each average year of data'

### Seasonal Pollution Rose for Langdale TRS



Object E-142 'Pollution roses for TRS at Langdale, showing each season'